The 360* Diabetes Solution : Science, Society and Self-care

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About The Book

Diabetes mellitus has emerged as one of the most significant public health challenges of the twenty-first century, affecting millions of individuals worldwide and imposing a substantial burden on healthcare systems, economies, and societies. Far beyond being a disorder of glucose metabolism, diabetes is a complex, multi-factorial condition that influences nearly every aspect of human health, including physical, psychological, social, and economic well-being. Recognizing the need for a comprehensive understanding of this growing epidemic, The 360° Diabetes Solution: Science, Society and Self-care presents an integrated and multidisciplinary exploration of diabetes from diverse perspectives.

This book is designed to provide readers with a holistic view of diabetes by combining scientific knowledge, clinical insights, nutritional approaches, lifestyle interventions, psychological dimensions, and public health strategies. Bringing together contributions from distinguished academicians, researchers, healthcare professionals, and subject experts, the volume serves as a valuable resource for students, educators, clinicians, public health practitioners, policymakers, and individuals interested in understanding and managing diabetes more effectively.

The book begins by establishing a strong conceptual foundation of diabetes, including its classification, pathophysiology, epidemiology, and risk factors. It further examines the intricate relationship between diabetes and various health complications, including neurological disorders, cardiovascular diseases, liver dysfunction, cancer, and metabolic abnormalities. By presenting evidence-based discussions on these interconnected conditions, the book highlights the systemic impact of diabetes and underscores the importance of early diagnosis and comprehensive management.

A major strength of this volume lies in its emphasis on nutrition and lifestyle as powerful tools for diabetes prevention and control. Dedicated chapters explore dietary interventions, functional foods, medicinal plants, nutraceuticals, Millets, Wheatgrass, gut microbiota, and other emerging nutritional approaches that can support glycemic control and overall metabolic health. These chapters demonstrate how informed dietary choices and healthy lifestyle practices can significantly reduce disease burden and improve quality of life.

The book also addresses the human and societal dimensions of diabetes. Topics such as mental health, positive psychological factors, physical activity, sports training, physiotherapy, and diabetes management across different stages of life emphasize the need for patient-centered and holistic care. By acknowledging the emotional and psychological challenges faced by individuals living with diabetes, the book promotes a more compassionate and sustainable approach to disease management.

In addition, the volume explores contemporary developments in healthcare, including digital health ecosystems and integrated chronic disease management. These chapters highlight the trans-formative role of technology, innovation, and interdisciplinary collaboration in improving healthcare delivery and patient outcomes. The inclusion of public health nutrition and community-based perspectives further broadens the scope of the book, emphasizing prevention, awareness, and population-level interventions.

The title, The 360° Diabetes Solution, reflects the book's central philosophy—that effective diabetes management requires a comprehensive approach encompassing science, society, and self-care. Scientific advances provide the foundation for understanding the disease, societal efforts create supportive environments and health systems, and self-care empowers individuals to take an active role in managing their health.

By integrating these dimensions, the book aims to bridge the gap between research and practice while encouraging readers to adopt a broader perspective on diabetes prevention and management. It serves not only as an academic resource but also as a guide for fostering healthier lifestyles, informed decision-making, and improved health outcomes.

Ultimately, The 360° Diabetes Solution: Science, Society and Self-care represents a collective effort to address one of the most pressing health challenges of our time. Through evidence-based knowledge, practical insights, and interdisciplinary perspectives, the book contributes to the ongoing global mission of reducing the burden of diabetes and promoting a healthier future for individuals and communities worldwide.

About the Editor

Srishti Maheshwari is a research scholar in the department of Home Science, Chhatrapati Shahu Ji Maharaj University, Kanpur. She is a dedicated academician, researcher, and emerging scholar in the field of Home Science. Her research interests primarily focus on the intersection of metabolic health, particularly diabetes, and psychological well-being,. She has contributed significantly to the academic community through multiple research publications in reputed national and international journals contributed several book chapters and actively serves as a peer review and scoups indexed journals, covering areas such as diabetes awareness, environmental risk factors, mental health, and nutritional deficiencies. She has also edited university academic resources, including the M.A. Home Science Question Bank Of CSJMU. She has serves as a peer reviewer for reputed national and international peer review journals. Her academic contributions reflect a multidisciplinary approach, integrating science, society, and self-care perspectives—core themes aligned with this edited volume.

As an editor, Srishti brings strong expertise in academic writing, content structuring, and curriculum development. She has experience in editing university-level academic materials and has contributed to scholarly book chapters addressing contemporary health challenges. Through this book, The 360° Diabetes Solution: Science, Society and Self-Care, she aims to provide a comprehensive platform that combines evidence-based research with practical strategies, promoting a holistic understanding of diabetes for researchers, practitioners, and the wider community.

About the Co-Editor's

Suraj Gupta is a Research Scholar in the Department of Education at Chhatrapati Shahu Ji Maharaj University, Kanpur. His academic work spans educational policy, artificial intelligence in education, Policy research, bibliometric,and Inter-disciplinary research linking learning systems with societal and behavioral outcomes. He has Published extensively in reputed journals and contributed to multiple edited volumes, with a focus on innovation, sustainability, and evidence-based practices. He has serves as a peer reviewer for reputed journals, including Springer Nature. His research also engages with themes such as mental well-being, student behavior, and systemic transformation—areas that intersect meaningfully with contemporary health challenges.

As Co-Editor of The 360° Diabetes Solution: Science, Society and Self-Care, he brings an interdisciplinary perspective that integrates scientific evidence, educational innovation, and health awareness. His editorial vision emphasizes accessible, evidence-based knowledge that empowers researchers, healthcare professionals, educators, and the wider community to advance holistic diabetes prevention, management, and self-care.

Co-Editor's

Prof. Archna Saxena is a distinguished academician and researcher with over 34 years of extensive experience in teaching and research. She holds an M.Sc. in Foods and Nutrition, is NET qualified, and has earned her Ph.D., reflecting her strong academic foundation and dedication to academic excellence. Her core areas of interest include Therapeutic Nutrition and Dietetics, where she has made significant contributions through teaching, research, and academic mentorship. Prof. Saxena has served as the Convenor of Home Science at C.S.J.M. University, Kanpur, and has also been actively associated as an IQAC/NAAC Coordinator for the past six years, contributing to quality assurance and institutional development. She is the author of a book on Nutrition, Health and Hygiene and has also written several book chapters in her field. In addition, she has played an important role in formulating NEP-based syllabus frameworks, aligning academic programs with contemporary educational standards. An accomplished researcher, Prof. Saxena has published 38 research papers in various reputed national and international journals. She is currently guiding seven research scholars working on diverse nutrition-related topics. She has also served as a member of the Board of Studies in several esteemed universities and has been invited as a thesis expert at various institutions. Her active involvement in organizing and participating in numerous workshops, seminars, and academic programs highlights her commitment to continuous learning and knowledge dissemination. With a career marked by scholarship, leadership, and dedication, Prof. Archna Saxena continues to inspire students and researchers through her valuable contributions to the field of nutrition and dietetics.

As Co-Editor of The 360° Diabetes Solution: Science, Society and Self-care, Prof. Saxena brings her extensive expertise in nutrition, therapeutic dietetics, and public health, enriching the volume with valuable academic insights and a multidisciplinary perspective on diabetes management and health promotion.

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Conceptual Framework of Diabetes

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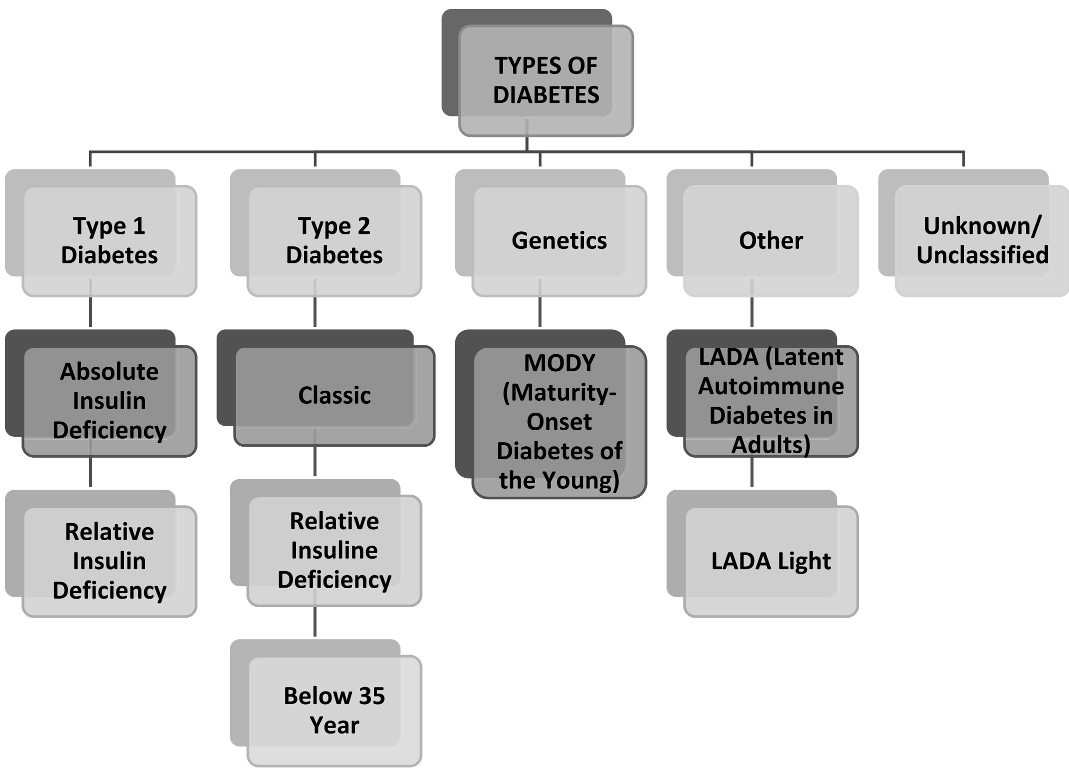
DEFINITION

Diabetes mellitus Diabetes mellitus is a chronic hyperglycemia caused either by defects in insulin secretion, or in insulin action, or both. It is a heterogeneous metabolic disorder that cannot be adequately classified and thereby abnormal clinical effects and results and requires a detailed classification to be accurately diagnosed and treated *(Yadav et al., 2025) (Bae et al., 2025)*. The conventional classification of diabetes has deeply involved Type 1 and Type 2 but new studies show that the disease has a complex spectrum beyond this dual classification *(Patil et al., 2023)*.

CLASSIFICATION



2.1 Type 1 Diabetes: Autoimmune Pathogenesis

Type 1 diabetes is caused by the autoimmune damage of pancreatic beta cells leading to an absolute or near-absolute lack of insulin *(Aamodt and Powers, 2025).* This autoimmune reaction is affected by the genetic predispositions and the environmental factors as well as though normally occurs in childhood, it can occur at any age. Autoantibodies of islet cell antigens and C-peptide level are essential to diagnosis *(Ozougwu, 2013).* Treatment involves lifelong insulin therapy using highly sophisticated machines like insulin pumps and continuous glucose monitoring systems, and lifestyle change *(Irakoze, 2024).*

2.2 Type 2 Diabetes: Insulin Resistance and Beta-Cell Dysfunction

In type 2 diabetes (T2DM), there are two fundamental defects, namely a defect of insulin secretion in beta cells and defect of insulin-insensitivity in peripheral tissues. It comprises more than 85 percent of the cases of diabetes in the world. Obesity, sedentary lifestyle, stress, aging and genetic susceptibility are the risk factors. The pathophysiology of the disease is complicated, including molecular processes that influence the insulin production, release, and activity *(Galicia-Garcia et al., 2020).* It is important to note that youth-onset T2DM has a different aetiology and progression and in most cases occurs at earlier stages resulting to earlier complications *(Titmuss et al., 2024).* The disease is also perpetuated by factors like imbalance in gut microbiota, and metabolic memory.

2.3 Other Forms of Diabetes and Heterogeneity

There are a number of non-Type 1 and Type 2:

- **Latent Autoimmune Diabetes in Adults (LADA):** A combination of autoimmune disease and Type 2 diabetes facets, Diabetes may be diagnosed later in life (after 35 years) and evidence of islet autoantibodies are present *(Jones et al., 2021).*
- **Single-gene defects, including HNF1A**, cause Maturity-Onset Diabetes of the Young (MODY), which causes diabetes in young people *(Valkovicova et al., 2019).*
- **Gestational Diabetes Mellitus (GDM)** is a malady that develops during pregnancy and impacts the health of both the mother and the infant *(Govindaswamy & P.s, 2022).*
- **Double Diabetes** has both autoimmune and metabolic characteristics, which are difficult to diagnose and treat *(Stone et al., 2024).*

The issue of raising awareness towards atypical diabetes types requires more stringent diagnostic standards and the identification of various endotypes. The new Diabetes Grade Stage Classification system incorporates pathophysiology and the severity of complications, which is better than the traditional classification weaknesses *(Bae et al., 2025)***.**

GLOBAL AND INDIAN EPIDEMIOLOGY

3.1 Global Burden and Epidemiological Trends

The prevalence of type 2 diabetes is a significant epidemic in the world, with more than 462 million individuals having the disease in 2017 (approximately 6.28% of the world population) *(Khan et al., 2019).* The incidence increases drastically as age increases to 22% in individuals aged 70 and above. It is estimated that the number will rise to 70-79 per 100,000 in 2030 *(Sun et al., 2023).* The level of diabetes incidence, mortality, and disability-adjusted life years (DALYs) have all increased considerably within the last three decades *(Yu et al., 2025).* It is worth noting that the prevalence of Type 1 diabetes shot up by 41.47 percent during the period of 1990-2021, with the mortality and DALYs dropping, signifying better management *(Xie et al., 2025).*

3.2 Indian Epidemiology and Disease Burden

India has bequeathed a very specific and dramatic diabetes epidemic, with the highest number of diabetes patients in the world *(Chauhan et al., 2025).* As of 2019, it was estimated that there were 77 million Indians with diabetes and nearly 134 million Indians with diabetes are anticipated by 2045 *(Pradeepa & Mohan, 2021).* Between 1990 and 2021, the number of incidence increased by 162.74 to 264.53 per 100,000 with a corresponding rise in mortality *(Chauhan et al., 2025).* Worryingly, approximately 57 percent of the cases of diabetes in India remain un-diagnosed making the disease control difficult. The prevalence is significantly higher in urban areas compared to rural regions as well as significantly inter-state. There are also wide disparities in the pre-diabetes rates *(Pradeepa & Mohan, 2021).* With this particularity, high levels of visceral fat with a low BMI (the so-called thin-fat phenotype) are common in India (43.3%), particularly in rural communities, and it puts them at risk of developing diabetes despite their thinness *(Ghadei et al., 2025).*

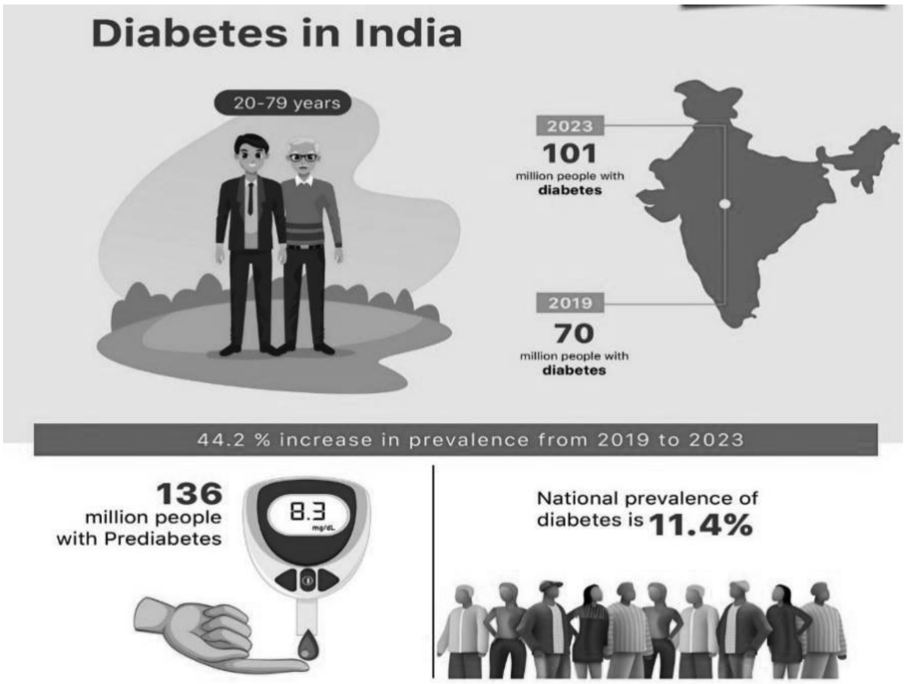


FIG.2: Indian Epidemiology and Disease Burden of Diabetes

3.3 Regional Variations and State-Level Disparities

Indian states located in the south and west, including Tamil Nadu and Goa, have the highest rates of diabetes and DALY *(Chauhan et al., 2025)*. There is an inverse relationship between malnutrition and prevalence of diabetes among states across state, an epidemiological transition. An example is that Jharkhand has a high level of malnutrition and increased diabetes as compared to Kerala, which has a poor level of malnutrition but high diabetes levels *(Ghadei et al., 2025)*. By 2031, the number of DALYs and prevalence of diabetes will rise significantly in the country. Some of the factors that cause differences among regions are diet, obesity, poor exercise, and lifestyle *(Pradeepa & Mohan, 2021)*. The rates of gestational diabetes also differ in various regions, with those in the south of India being higher compared to those in the north and east *(Zade et al., 2025)*.

3.4 Complications and Disease Impact

In India, diabetes complications are one of the significant problems of the population. The prevalence rates of diabetic retinopathy range between 4.8 and 21.7, the prevalence rate of nephropathy is between 0.96 and 2.3, and the prevalence rate of neuropathy is between 10.5 and 44.9 *(Govindaswamy & P.s, 2022)*. Type 2 diabetics around the world have the highest burden of diabetic kidney disease (DKD) with the highest burden in Asia and middle sociodemographic groups *(Deng et al., 2021)*. Youth-onset diabetes patients have a high retinal abnormality *(Jensen et al., 2023)*. Microvascular (eye, kidney, nerve) and macro (heart, brain) complications are significant causative agents of morbidity and mortality in diabetics *(Lu et al., 2023),* and cardiovascular disease causes the death of more than three-quarters of patients with diabetes *(Laakso, 2010)*.

GENETIC, ENVIRONMENTAL, AND LIFESTYLE DETERMINANTS

4.1 Genetic Factors and Hereditary Influences

Diabetes has genetic predisposition as its key factor because it contributes between 40 -80 percent to Type 2 diabetes risk. The presence of family history is quite a strong risk factor, and the primary genes, which influence the insulin pathways, and the risk of the disease, are TCF7L2, PPARG, KCNJ11 and FTO *(Nyakairu, 2024)*. The most closely related gene is TCF7L2 especially *(Grant et al., 2010)*. Monogenic forms of diabetes including MODY attributed to single-gene mutations indicate the significance of the single-gene mutation in the early-onset diabetes. The situation in hereditary genetic susceptibility is rather equal as it is transferred by both parents *(Meigs et al., 2000)*. Another reliance on polymorphisms of TCF7L2 is gestational diabetes. Polygenic risk scores (PRS) do not provide much predictive value since the disease is intricate, and they assist in screening people at risk *(Zhang et al., 2022)*. Epigenetic modifications that are environmentally induced also form further genetic risk modulation. There are predisposing HLA genotypes in Type 1 diabetes (e.g. HLA-DR3/DQ2, DR4/DQ8) *(Leelavathi and Sivakami, 2025)*.

4.2 Obesity and Dietary Determinants

The growing prevalence of diabetes around the world can be compared to the rate of increasing obesity and unhealthy lifestyle *(Patil et al., 2023)*. Obesity results because of both genetic and environmental factors where lifestyle is a dominant phenotype determinant. The availability of foodstuffs with high amounts of calories and low amounts of nutrients has contributed to the increase of obesity *(Jebb et al., 2007)*. The quality of the diet affects the risk of diabetes: a high level of saturated fats and fructose worsens intrahepatic fat *(Hydes et al., 2021),* and Mediterranean-style diets enhance the regulation of glucose *(Gioxari et al., 2022)*. The consumption of fruit and vegetables prevents the excess weight gain, and the risk of obesity may be lowered by limiting the consumption of sugary-sweetened drinks *(Sohi et al., 2023)*. Combining diet and exercise lowers the benefits of physical activity in the presence of pro-inflammatory diets *(Shi et al., 2023)*. Dietary interventions are effective when they are based on the composition of macronutrients with priority on fibre and minimizing refined carbohydrates *(Espinola et al., 2025)*.

4.3 Physical Activity and Sedentary Behaviour

One of the keys to the prevention and treatment of diabetes is exercise *(Espinola et al., 2025)*. The results of physical activity and exercise are a negative and constant relationship with diabetes risk, and even moderate-vigorous exercise has a declining impact on the risk of obesity. The value of leisure-time activities (walking and cycling) is higher than the value of occupation *(Sohi et al., 2023)*. Inactive lifestyles, specifically, prolonged sitting and TV viewing are risk factors that lead to diabetes by themselves *(Kolb and Martin, 2017)*. Poor sleep is also a modifiable factor of diabetes particularly among shift workers and it is a risk factor of diabetes *(Hulsegge et al., 2021)*. One of the effective methods of reducing the risk of cardio metabolic diseases is the restoration of physical activity in the dietary changes *(Pathirana et al., 2025)*. The level of physical activity and diabetes prevalence are environmental determinants of the neighbourhood layout, leisure amenities and elevation *(Farooq et al., 2025) (Ahamd et al., 2025)*.

4.4 Gene-Environment Interactions and Comprehensive Risk Factors

There are complicated interactions between genetic predisposition and lifestyle/environmental factors that lead to diabetes risk *(Zhang et al., 2024)*. The protective genetic variants can improve the response to dietary interventions, whereas the risk alleles can regulate the metabolic response to diet *(Kuo et al., 2025)*. Genetic risk alleles and familial history are coexisting, which enhances glycaemic pathological conditions *(Gautier et al., 2011)*. Individuals that are genetically predisposed experience higher levels of oxidative stress and inflammation after meals. The socioeconomic status, housing conditions, and the availability of healthy foods and physical activities are also social determinants of diabetes that play a critical role *(Baig et al., 2020)*. Socio-environmental disadvantages in the form of polysocial risk scores are also predictive of genetic scores, and differ by ethnicity *(Naderian et al., 2025)*. To prevent and provide individual care, it is crucial to combine genetic, environmental, behavioural, and socioeconomic factors *(Jang et al., 2025) (Ye et al., 2021)*.

CONTEMPORARY UNDERSTANDING OF DIABETES CLASSIFICATION

5.1 Evolution Beyond Traditional Type 1 and Type 2 Categories

Conventional typology of diabetes as Type 1 (autoimmune) and Type 2 (metabolic) does not satisfactorily describe the complexity of the disease *(Bae et al., 2025).* Several patients exhibit the convergence of features, which obliterate the category lines. It has been supported by emerging evidence that Type 2 diabetes pathophysiology is immune-involved *(BrooksWorrell & Palmer, 2010).* The identification of unusual types of diabetes has improved the knowledge about insulin production, resistance, and autoimmunity *(Stone et al., 2024).* More accurate prediction and management of diabetic complications can be achieved with the help of novel classification systems, which include five-subtypes model created by Almqvist on the basis of pathophysiology and risks of complication *(Tanabe et al., 2024).* Machine learning has enabled predicting subtypes with a high level of reliability through the use of easily accessible clinical data, which is useful in the treatment of individuals *(Bae et al., 2025).*

5.2 Subtype-Specific Management Implications

Different subtypes of diabetes possess different metabolite characteristics and risk of complications, and thus, should not be treated in the same manner. Insulin unsensitised patients should be treated with SGLT2, thiazolidinedione or GLP -1 receptors, and insulin or secretagogues in patients with beta -cell insufficiency. GIP/GLP-1-agonist is especially applicable in the case of the obese patients in the danger of hepatic steatosis. Nonetheless, the treatment of the first-line remains the same metformin, regardless of the subtypes *(Reyes-Medina et al., 2025).* Severe insulin-deficient and autoimmune diabetes clusters are more likely to have proliferative retinopathy and chronic kidney disease, and even higher chances of nephropathy exist with the insulin-resistant subgroups of obesity *(Fedotkina et al., 2021).* TCF7L2 risk alleles are an expertise in genetics that is utilized in the prediction of the time, and the type of intensive treatment required *(Gautier et al., 2011).* Specialized diagnostic classification enhances the process of resource allocation in treatment and the prognosing outcomes *(Reyes-Medina et al., 2025).*

SYSTEMIC FACTORS AND FUTURE DIRECTIONS

6.1 Health System Challenges in India

The problem of inadequate healthcare systems contributes to the rising rate of diabetes in India. There are limited health centres that have adequate lab facilities to screen oral glucose tolerance due to which the screening of gestational diabetes is done. The majority of the facilities lack uniform processes of screening and management, and postpartum follow-ups are inadequate *(Zade et al., 2025)*. Nearly half of the impacted families are financially unable to cope due to the cost of diabetes treatment. The dual burden of malnutrition and diabetes does not exist, but rather it disrupts the compartmentalized health programs. BMI screening excludes a considerable proportion of the thin-fat diabetics. Otherwise, the healthcare providers themselves are not necessarily trained to address this complex interaction, and thus they have to be educated about the capacity building as well as the need to be trained in that matter is urgent *(Ghadei et al., 2025)*.

6.2 Policy and Implementation Strategies

In India, as well as in the rest of the world, there is a need to reduce the burden of diabetes with the help of effective, evidence-based policies *(Montoya et al., 2024)*. They ought to integrate the delivery of improved access to healthcare with lifestyle change and primary prevention in the community *(Chauhan et al., 2025)*. Systematic screening and early clinical treatment should be combined with health promotion in order to put an end to the epidemic and contain complications *(Pradeepa & Mohan, 2021)*. Online health technologies have a potential yet face several challenges, including the limited rural phone coverage and insufficient medical staff training *(Zade et al., 2025)*. The aspect of health disparities demands the introduction of equity-based, culturally sensitive, and community-focused interventions *(R et al., 2025)*. Two aspects to be considered together to prevent Type 2 diabetes are malnutrition and metabolic dysfunction, which need to be addressed *(Ghadei et al., 2025)*.

SUMMARY

Diabetes mellitus is a multifaceted chronic disease, which is marked by hyperglycemia, which happens as a result of insulin secretion and/or activity deficits. The issues of Type 1 and Type 2 are so complicated that they cannot be adequately covered with the help of traditional categories. Diabetes type 1 is an autoimmune condition, whereby the pancreatic beta-cells are destroyed, and the patient needs insulin throughout life. Type 2 Diabetics which is the most prevalent conditions comprises insulin resistance and progressive dysfunction of the beta-cell that happens as a result of obesity, lifestyle and genetics. Other forms of heterogeneity, like LADA, MODY, gestational diabetes and double diabetes accelerate the heterogeneity. The proliferation of diabetes in the world and specifically in India is increasing at an unbelievable rate such that even those who are not yet diagnosed with the disease are languishing in pathetic conditions. The level of genetic disposition is also significant and can be altered by the effects of lifestyle practices such as nutrition and physical exercises. The contemporary models of classification extend to out of the traditional categories in a bid to enable the treatment of the patients on a personalized approach. The proposed policy has a systematic healthcare issue that India faces, being in need of a blend of policies that are culturally relevant and are bound to bring about success in reducing the dual burden of malnutrition and diabetes.

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Diabetes And Neurological Disorder

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1.) Introduction: The Neurological-Metabolic Connection

Diabetes mellitus is becoming recognized not simply as a metabolic failure of glucose homeostasis, but as a gradual neurological catalyst that damages the structural integrity of both the peripheral and central nervous systems. Driven by the deadly synergy of persistent hyperglycemia, oxidative stress, and micro vascular ischemia, the disease operates as a "silent circuit breaker" that destroys key signaling pathways. Although peripheral neuropathy continues to be the most prevalent clinical manifestation, autonomic dysfunction and accelerated cognitive decline are also part of the illness, which is also referred to in developing research as "Type 3 diabetes." The accumulation of advanced glycation end products (AGEs), which cause neuroinflammation and axonal degeneration, and the activation of the polyol pathway cause this neurological deterioration. As a result, the neurological system becomes the principal site of harm in the diabetic condition, where the loss of metabolic control directly results in the loss of motor, sensory, and cognitive function. In order to reinterpret diabetes as a systemic neurodegenerative disease, this chapter investigates the molecular interaction of endocrinology and neurology.

2.) Anatomical aspects

Brain Axis and Diabetes

A complicated, two-way mechanism known as the Diabetes-Brain Axis defines the connection between diabetes mellitus and the brain. The anatomical and functional integrity between the central nervous system (CNS) and systemic glucose control is represented by this axis. The brain uses nearly 20% of the body's glucose despite making up only 2% of the body weight, making it particularly susceptible to the metabolic swings that are typical of diabetes.

Structural Integrity and the Blood-Brain Barrier (BBB)

The Blood-Brain Barrier is the main contact of the diabetes-brain axis. Long-term hyperglycemia causes tight junction proteins (such as occludin and claudin-5) to be overexpressed and basement membrane proteins to become glycated. This barrier permits poisons and peripheral inflammatory cytokines to enter the brain parenchyma, causing microglial activation and persistent neuroinflammation.

The Axis's Structural Elements

Three distinct regions of the brain are usually affected by diabetes:

The Hippocampus: This area is very sensitive to insulin resistance and is essential for memory and learning. Oxidative stress brought on by diabetes causes dendritic atrophy and decreased neurogenesis, which frequently shows up as macroscopic hippocampus shrinkage.

The Hypothalamus: As the "metabolic thermostat," the hypothalamus detects insulin and glucose levels in the blood. A feedback loop that exacerbates systemic hyperglycemia is created when hypothalamus inflammation interferes with the signals that typically inhibit hunger and promote hepatic glucose production in a diabetic condition.

The White Matter Hyperintensities (WMH):): Diabetes is characterized by small vascular disease, which causes lesions in the white matter of the brain. Executive dysfunction is exacerbated by these anatomical "disconnects" that impede the quick transmission of impulses between various cortical regions.

The Type 3 Diabetes Concept: Many researchers now categorize the ensuing cognitive deterioration as Type 3 Diabetes because the structural degradation seen in the diabetes-brain axis is so comparable to the pathophysiology of Alzheimer's disease, particularly with regard to poor insulin signaling and amyloid-beta accumulation. This demonstrates that the brain is not merely a recipient of diabetes, but also actively participates in its evolution.

1. Physiological aspects

Hypothalamic-Pituitary-Adrenal (HPA) axis

Diabetes and Neurological Disorders

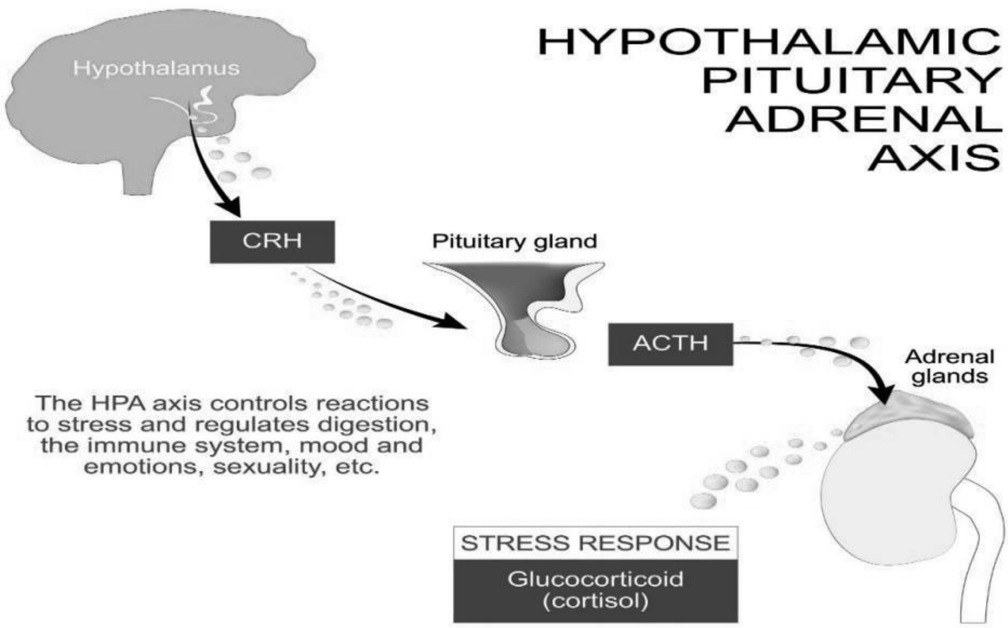
Both Type 1 Diabetes (T1D) and Type 2 Diabetes (T2D) are inextricably linked to neurodevelopmental abnormalities, structural brain alterations, and progressive cognitive decline.

Lifespan Cognitive Impact: Cognitive abnormalities manifest at every stage of life in diabetic patients. The brain's heavy reliance on glucose and insulin makes neurons highly susceptible to damage from chronic hyperglycemia and impaired insulin signaling.

Type 1 Diabetes (T1D) and Neurodevelopment: Because T1D often presents during critical periods of brain development, it can disrupt early neurogenesis. This leads to lasting deficits in memory, processing speed, and overall IQ, exacerbated by episodes of diabetic ketoacidosis and chronic high blood sugar.

Type 2 Diabetes (T2D) and Neurodegeneration: Driven largely by lifestyle variables, T2D is characterized by brain insulin resistance. This leads to significant cognitive deterioration—particularly in memory and executive function—and is anatomically correlated with structural changes such as hippocampal shrinkage.

The Role of the HPA Axis:



The hypothalamic-pituitary-adrenal (HPA) axis is a primary driver of diabetes-related cognitive deficits. Dysregulation of this axis in both T1D and T2D leads to elevated glucocorticoid levels. This chronic stress response impedes neurogenesis and accelerates hippocampal atrophy.

2. The impact of glycemic variability on nerve health:

The mechanism behind nerve damage (neuropathy) driven by glycemic variability largely comes down to cellular stress and restricted blood flow.

The Oxidative Stress Engine: Reactive oxygen species, or free radicals, are overproduced when blood glucose levels fluctuate quickly. Blood sugar fluctuations cause a "oxidative stress engine." Nerve cells' proteins and DNA are directly harmed by this stress, which eventually leads to their degeneration.

Depriving the Nerves (Endothelial Dysfunction): Because nerves are living tissue, they need a steady flow of nutrients and oxygen, which are supplied by microscopic blood vessels called the vasa nervorum. These tiny blood capillaries harden or shrink as a result of severe glucose changes damaging their biological lining. As a result, the blood supply is effectively cut off, starving the nerves.

Inflammatory Cascade: An immunological reaction brought on by a blood sugar fluctuation results in low-grade, systemic inflammation. Nerve impulses may slow down, malfunction, or stop entirely as a result of this inflammation attacking the myelin sheath, the protective covering that surrounds your nerve fibers.

Mitochondrial Damage: The mitochondria in nerve cells are overloaded by the drastic metabolic changes necessary to deal with quickly fluctuating glucose levels, which eventually results in energy depletion and cell death.

There are two main ways that glycemic fluctuation can harm the neurological system:

Peripheral Neuropathy: This is the most prevalent symptom, typically affecting the hands, arms, feet, and legs. Sensory symptoms like "pins and needles" tingling, burning, numbness, or sharp, shooting pains are brought on by the injury.

Autonomic Neuropathy: This affects the nerves that control your body's involuntary functions. Damage here can lead to issues with heart rate regulation, blood pressure drops when standing, digestive problems (like delayed stomach emptying, or gastroparesis), and bladder dysfunction.

3. Pathophysiology: The Cellular Mechanics of High Blood Sugar

Oxidative Stress and Inflammation: Chronic hyperglycemia initiates profound cellular toxicity primarily within insulin-independent tissues—such as endothelial cells, neurons, and renal mesangial cells—where glucose permeates the plasma membrane unhindered. This passive, unchecked influx supersaturates intracellular metabolic machinery, shunting excess glucose into alternative, pathological biochemical cascades. Foremost among these is the overactivation of the electron transport chain, which precipitates mitochondrial dysfunction and the rampant overproduction of reactive oxygen species (ROS). Concurrently, the surplus glucose forces activation of the polyol pathway, wherein the enzyme aldose reductase converts glucose into sorbitol, leading to severe osmotic stress and the depletion of endogenous antioxidant reserves like reduced glutathione. Furthermore, the elevated intracellular glucose concentration accelerates non-enzymatic glycation, culminating in the irreversible accumulation of advanced glycation end-products (AGEs). These AGEs cross-link essential extracellular matrix proteins and persistently activate their specific cellular receptors (RAGE), thereby propagating chronic localized inflammation. Simultaneously, excess glycolytic intermediates are diverted into the hexosamine pathway, inducing detrimental epigenetic shifts and altering structural protein function via excessive O-GlcNAcylation. This metabolic dysregulation also triggers the aberrant activation of protein kinase C (PKC), an enzyme cascade that directly degrades vascular integrity, alters hemodynamics, and promotes pro-fibrotic signaling. Synergistically, these intersecting mechanisms—oxidative stress, osmotic imbalance, and structural protein degradation—overwhelm the cell's intrinsic reparative capacities. Ultimately, this sustained metabolic trauma orchestrates progressive cellular apoptosis and drives the characteristic microvascular and neuropathic complications prevalent in chronic diabetic pathology.

The Polyol Pathway: The polyol pathway is a crucial metabolic route that becomes highly active during states of chronic hyperglycemia, and it is a leading contributor to the microvascular complications of diabetes, particularly impacting tissues that absorb glucose independently of insulin, such as the peripheral nerves, the lens of the eye, and the kidneys.Under normal physiological conditions, glucose is primarily metabolized via the glycolytic pathway. However, when circulating glucose levels overwhelm the cell's capacity for glycolysis, the excess intracellular glucose is diverted into the accessory polyol (or sorbitol) pathway.This pathway proceeds in two enzymatic steps:Reduction of Glucose to Sorbitol: In the first step, the enzyme aldose reductase (AR) utilizes the cofactor NADPH (nicotinamide adenine dinucleotide phosphate) to reduce glucose into the sugar alcohol sorbitol. While this enzyme has a relatively low affinity for glucose, the saturation of tissues by hyperglycemic states forces this reaction into overdrive.Oxidation of Sorbitol to Fructose: Normally, sorbitol is then converted into fructose by the enzyme sorbitol dehydrogenase (SDH), using the cofactor NAD+.The Sorbitol Trap and Osmotic StressThe central pathophysiological problem arises because of the disparity in the kinetics of these two enzymes. Aldose reductase works efficiently at converting glucose to sorbitol, whereas sorbitol dehydrogenase is much slower at converting sorbitol to fructose.Furthermore, sorbitol itself is a highly polar, hydrophilic molecule. It possesses limited ability to diffuse across the cellular plasma membrane and cannot be easily pumped out by the cell.Consequently, sorbitol begins to relentlessly accumulate within the intracellular space. Because sorbitol is highly osmically active, this massive buildup induces intense osmotic stress.This osmotic stress forces the cell to compensate:Intracellular Swelling: Water is drawn into the cell by the high concentration of sorbitol, leading to severe intracellular swelling (hypertrophy). This swelling is a primary mechanism behind the development of diabetic cataracts, as the over-hydration alters the physical structure of the lens fibers.Dysregulation of Intracellular Ion Concentrations: The influx of water disrupts the delicate balance of ions (such as sodium and potassium) and molecules like myo-inositol, which are critical for maintaining the cell's electrochemical gradient. In neurons, this disruption impairs the conduction of nerve impulses, directly contributing to the pain and loss of sensation characteristic of diabetic neuropathy.Co-pathology: NADPH DepletionCritically, the polyol pathway's impact extends beyond osmotic stress. The first reaction consumes NADPH at an aggressive rate. NADPH is the essential cofactor for another vital enzyme, glutathione reductase, which is responsible for regenerating the cell's primary antioxidant, reduced glutathione.By competitively consuming NADPH, the polyol pathway severely depletes the cell's antioxidant reserves. This fatally compromises the cell's ability to neutralize free radicals, making it extremely vulnerable to the overwhelming oxidative stress simultaneously generated by mitochondrial overload.Thus, the polyol pathway creates a multi-pronged metabolic crisis: physically distorting the cell through osmotic swelling while simultaneously stripping away its defenses against oxidative damage.

Advanced Glycation End-products (AGEs)

The human brain relies on a highly dynamic and flexible intracellular architecture to maintain synaptic plasticity, transport neurotransmitters, and preserve cognitive function. In the context of diabetes mellitus, this delicate mechanical environment is severely threatened by chronic hyperglycemia. Elevated blood glucose acts as a relentless catalyst for glycation, a process that culminates in the formation of Advanced Glycation End-products (AGEs). By forcibly cross-linking structural and functional proteins, AGEs effectively "stiffen" the neural landscape, driving the pathogenesis of diabetic neuropathy and diabetes-associated cognitive decline (diabetic encephalopathy).

Microvascular Damage: Peripheral nerves rely on a delicate microscopic vascular network known as the vasa nervorum to deliver essential oxygen and nutrients. In diabetes, chronic hyperglycemia creates a toxic environment that relentlessly damages the inner endothelial lining of these fragile blood vessels. This persistent cellular stress forces the capillary basement membranes to unnaturally thicken in a misguided attempt at structural repair. Consequently, this thickening significantly narrows the internal diameter of the vessels, mechanically restricting the volume of blood able to pass through. Furthermore, elevated glucose severely depletes the availability of nitric oxide, a vital molecule that normally allows blood vessels to relax and expand. Deprived of nitric oxide, the vasa nervorum becomes trapped in a state of rigid constriction, severely compounding the mechanical blockage. This combination of narrowed and constricted vessels triggers profound localized ischemia, systematically starving the peripheral nerves of vital blood flow. Without adequate oxygen delivery, nerve cells suffer from severe hypoxia and lose their ability to generate the ATP required for basic metabolic survival. This energy crisis initiates the rapid deterioration of protective Schwann cells, causing the nerves to lose their critical myelin insulation. Ultimately, this chronic starvation forces the unprotected nerve axons to progressively wither and die, directly causing the debilitating sensory loss of diabetic neuropathy.

4. Neurological Complication Of Diabetes

- **Early complication**

  a) **Diabetic Peripheral Neuropathy (DPN):** Diabetic Peripheral Neuropathy (DPN) is a progressive and debilitating neurological complication resulting from prolonged, uncontrolled high blood sugar. Chronic hyperglycemia systematically damages the peripheral nervous system by unleashing widespread oxidative stress and inflammatory cascades within nerve tissues. The relentless accumulation of Advanced Glycation End-products (AGEs) further accelerates this decay by stiffening structural proteins and disrupting essential cellular transport. Simultaneously, the delicate microvascular network supplying these nerves becomes severely constricted and damaged, leading to chronic localized ischemia. Starved of essential oxygen and nutrients, the longest nerve fibers in the body begin to misfire and slowly degenerate over time. This structural degradation typically manifests first in the toes and feet, progressing upward in a characteristic "stocking-glove" pattern of sensory impairment. Patients frequently experience an agonizing spectrum of symptoms, ranging from sharp, burning nerve pain to profound numbness and tingling. As the protective sensation completely fades, individuals lose the crucial ability to detect minor cuts, blisters, or thermal injuries on their extremities. This profound sensory deficit creates a highly dangerous environment where unnoticed wounds can quickly evolve into severe, non-healing foot ulcers. Ultimately, without early intervention and strict glycemic control, DPN significantly increases the risk of catastrophic lower-limb amputations.

b) **Distal Symmetric Polyneuropathy:** Distal Symmetric Polyneuropathy (DSPN) represents the most prevalent clinical manifestation of diabetic nerve damage, universally recognized by its hallmark stocking-glove pattern of sensory impairment. This highly predictable progression is not random, but rather the direct result of a physiological vulnerability known as length-dependent axonal degeneration. The human body's longest nerve fibers—those stretching from the lower spinal cord to the very tips of the toes—demand a tremendous and uninterrupted supply of metabolic energy to sustain vital intracellular transport over such vast distances. When chronic hyperglycemia, oxidative stress, and microvascular ischemia systematically strangle this energy supply, the neurons undergo a pathological dying-back process, causing the furthest distal terminals to starve and deteriorate first. Consequently, patients initially experience the onset of numbness, tingling, or agonizing burning pain in their toes, which relentlessly marches upward through the feet and lower legs to create a distinct sensory deficit mirroring the shape of a stocking. As the systemic metabolic exhaustion advances, the slightly shorter nerve fibers supplying the upper extremities eventually succumb to the same fate, causing parallel symptoms to emerge in the fingers and hands to form the corresponding "glove" distribution. This symmetrical, ascending loss of sensation profoundly impairs proprioception and natural protective pain reflexes, tragically rendering the extremities highly susceptible to silent mechanical trauma, chronic ulceration, and severe secondary infections.

c) **Small Fiber vs. Large Fiber Damage:** To fully understand the clinical spectrum of diabetic neuropathy, it is essential to recognize that the peripheral nervous system utilizes two anatomically and functionally distinct "cables" to transmit information: small fibers and large fibers. Chronic hyperglycemia damages both, but the resulting clinical symptoms differ drastically depending on which fibers are currently deteriorating. Small Fiber Damage: The Loss of Pain and Temperature Small nerve fibers, which include unmyelinated C-fibers and thinly myelinated A-delta fibers, act as the body's primitive alarm system. Their primary responsibility is to transmit sharp pain, dull aches, and thermal sensations (hot and cold). Because they lack a robust, protective myelin sheath, these delicate fibers are often the very first casualties of the metabolic toxicity and micro vascular ischemia associated with diabetes. When small fibers degrade, the resulting damage is highly localized to the skin and typically presents as a paradoxical mix of numbness and agonizing "positive" symptoms. Patients frequently report spontaneous, searing, burning pain, electric shock-like sensations, and allodynia (where a normally painless stimulus, like the brush of a bed sheet, becomes excruciatingly painful). Crucially, the destruction of small fibers neutralizes the patient's ability to distinguish temperature, rendering the feet highly vulnerable to severe, unnoticed burns from bathwater or heating pads. Large Fiber Damage: The Loss of Vibration and Proprioception Conversely, large nerve fibers (A-beta fibers) are thick, heavily myelinated, and designed for rapid signal conduction. They are responsible for transmitting mechanical information, specifically vibration sensation, light touch, and proprioception (the brain's subconscious awareness of joint position and spatial orientation). As diabetic damage eventually overcomes their thick myelin insulation, the clinical presentation shifts from active pain to profound sensory voids. Large fiber neuropathy strips away the mechanical feedback loop between the feet and the brain. Patients lose the ability to feel the vibration of a tuning fork during a clinical exam, and more dangerously, they lose the ability to feel the ground beneath them. This specific loss of proprioception profoundly impairs balance, resulting in an unsteady, wide-based gait. Without the ability to detect mechanical pressure or friction, abnormal weight-bearing forces go completely unnoticed, setting the immediate stage for the formation of severe, limb-threatening diabetic foot ulceration loss.

d) **Distal Symmetric Polyneuropathy (DSPN)** is often dominated by sensory chaos. As the peripheral nerves succumb to metabolic starvation and ischemia, they do not simply go quiet; they begin to spontaneously misfire.

e) **Paresthesia (Tingling and Prickling):** In the early stages of nerve distress, patients frequently report a persistent "pins and needles" sensation. This tingling is the direct result of damaged, hyper-excitable nerves spontaneously discharging action potentials without any external physical stimulus.

f) **The "Burning Feet" Syndrome:** As the delicate, unmyelinated small nerve fibers degenerate, the patient's internal thermal and pain regulation fails. This manifests as a severe, relentless burning sensation, typically localized to the soles of the feet. Tragically, this neuropathic pain is often most severe at night, drastically impairing sleep and severely diminishing the patient's overall quality of life.

g) **Profound Numbness:** As the disease inevitably progresses and the larger nerve fibers die off, the burning and tingling are gradually replaced by a dense, heavy numbness. The feet feel as though they are wrapped in thick cotton or perpetually "asleep." It is at this precise moment—when the pain fades and the numbness takes over—that the patient enters the most dangerous phase of the disease.

- **Late Complications:** When diabetic neuropathy silences this alarm system, the consequences for the lower extremities are physically catastrophic.

  1. Diabetic Foot Ulcers: A diabetic foot ulcer is the direct, mechanical consequence of walking on a profoundly numb foot. Without the protective feedback loop of pain, minor daily traumas go completely unnoticed. A pebble in a shoe, a poorly fitting sneaker, or a small blister from friction can silently erode the skin over hours or days. Because large-fiber neuropathy also destroys proprioception, the patient's gait becomes altered, placing immense, unnatural pressure on specific areas of the foot (like the metatarsal heads). This repetitive mechanical stress grinds away at the insensitive tissue, eventually punching a hole through the dermis. Compounded by poor micro vascular circulation—which prevents vital immune cells and oxygen from reaching the wound—these ulcers are highly resistant to healing and serve as the primary gateway for severe bone infections (osteomyelitis) and eventual amputation.

  2. Charcot Neuroarthropathy (The Charcot Foot) resistance and Alzheimer's disease (often called Type 3 Diabetes). Stroke Risk is to increased vulnerability to ischemic and hemorrhagic events.

6. Diagnostic Tools and Screening

- **Physical Exam:** Monofilament testing and tuning fork assessments.

  1. The 10-Gram Monofilament Test: Detecting the Loss of Protective Sensation. The Semmes-Weinstein monofilament test is the gold standard for predicting a patient's risk of developing a diabetic foot ulcer. It specifically evaluates the integrity of the large nerve fibers responsible for detecting physical pressure and light touch.

Technique:

Tool: The clinician uses a standardized nylon filament calibrated to exert exactly 10 grams of linear force when pressed to the point of bending.

The Application: With the patient resting supine and their eyes closed, the clinician applies the monofilament perpendicular to the skin at specific, high-risk pressure points on the plantar surface of the foot (most commonly the first, third, and fifth metatarsal heads, and the plantar surface of the great toe).

The Buckle: The filament is pushed against the skin just until it gently buckles into a " C " shape and is held for one to two seconds. The patient is asked to simply say "yes" every time they feel the pressure.

Clinical Significance: The 10-gram threshold is not arbitrary; it represents the exact amount of pressure required to trigger a normal protective pain reflex. If a patient cannot feel the buckled filament at one or more sites, they are officially diagnosed with a Loss of Protective Sensation (LOPS). This confirms they can no longer feel the mechanical friction of a tight shoe or a pebble, placing them at an imminent risk for ulceration.

The 128-Hz Tuning Fork Assessment: The Early Warning System- While the monofilament tests for pressure, the tuning fork evaluates vibratory sensation. Because the longest, thickest, heavily myelinated large nerve fibers are required to rapidly transmit the complex mechanical signals of vibration, they are often the first to show measurable signs of metabolic decay.

Technique:

Tool: A specific 128-Hz medical tuning fork is used, as this frequency best stimulates the specialized mechanoreceptors (Pacinian corpuscles) in the skin and deep tissues.

Application: The clinician strikes the prongs to initiate a strong vibration and places the base of the vibrating fork firmly against a bony prominence at the furthest distal point of the body—typically the top of the joint of the big toe (the dorsum of the interphalangeal joint of the hallux).

Assessment: The patient (with eyes closed) must first confirm they feel the vibration, not just the cold metal or the pressure. Then, they are instructed to tell the clinician the exact moment the vibration completely stops.

Clinical Significance: The clinician often keeps their finger under the patient's toe to feel the vibration simultaneously. If the clinician can still clearly feel the tuning fork vibrating for several seconds after the patient reports it has stopped, it indicates an abnormal vibratory threshold. Because vibration sense degrades before protective touch, an abnormal tuning fork test is frequently the very first measurable, objective sign of Distal Symmetric Polyneuropathy (DSPN).

Electrophysiology: 1. Nerve Conduction Studies (NCS) and 2. Electromyography (EMG).

Electrophysiological testing—specifically Nerve Conduction Studies (NCS) and Electromyography (EMG)—is the gold standard for diagnosing, characterizing, and tracking the progression of diabetic neuropathy.Diabetic neuropathy most commonly presents as a distal symmetric sensorimotor polyneuropathy. Pathologically, it is primarily a length-dependent axonal neuropathy (meaning the longest nerve axons degrade first, starting at the feet), though secondary demyelination can occur as the disease progresses.

1. Nerve Conduction Studies (NCS) NCS assesses the physiological health of the peripheral nerves by stimulating them with small electrical shocks and recording the nerve's response. It specifically tests large myelinated sensory and motor nerve fibers.Key Parameters Evaluated:Amplitude: Reflects the number of functioning nerve fibers (axons).Conduction Velocity & Latency: Reflects the integrity of the myelin sheath.Typical NCS Findings in Diabetic Neuropathy:Decreased Amplitudes (Hallmark): Because diabetic neuropathy is an axonal disease, the primary finding is a drop in the amplitude of the electrical signals.Sensory Nerves: Decreased Sensory Nerve Action Potentials (SNAPs). The sural nerve (in the calf/foot) is often the earliest to show abnormalities.Motor Nerves: Decreased Compound Muscle Action Potentials (CMAPs) in distal nerves, such as the peroneal and tibial nerves in the legs.Mildly Slowed Conduction Velocities: While massive drops in speed usually indicate primary demyelinating diseases (like Guillain-Barré or CIDP), diabetic neuropathy can cause mild slowing of conduction velocities and slightly prolonged distal latencies due to the loss of the fastest-conducting large myelinated fibers and secondary demyelination.Length-Dependent Pattern: Abnormalities are worst in the lower extremities (feet and legs) and may be entirely normal in the upper extremities (hands and arms) during the early stages of the disease.Absent F-waves/H-reflexes: These late responses (which test the entire length of the nerve, including nerve roots) are often prolonged or absent early in the disease course.

Electromyography (EMG)

Needle EMG involves inserting a thin needle electrode directly into specific muscles to record their electrical activity at rest and during voluntary contraction. It evaluates the integrity of the motor unit (the motor neuron, its axon, and the muscle fibers it innervates).

- Typical EMG Findings in Diabetic Neuropathy: In diabetic neuropathy, the dying back of motor axons leaves muscle fibers detached from their nerve supply (denervation). Over time, surviving adjacent nerves branch out to "rescue" these orphaned fibers (reinnervation). EMG detects both of these processes.
- Abnormal Spontaneous Activity (At Rest): When the muscle is completely relaxed, a healthy muscle is electrically silent. In diabetic neuropathy, active axonal loss causes orphaned muscle fibers to spontaneously fire. The EMG picks this up as fibrillation potentials and positive sharp waves (PSWs).
- Abnormal Voluntary Activity (During Contraction): Reduced Recruitment: Because there are fewer functioning motor nerves, fewer motor units activate when the patient tries to flex the muscle.
- Large, Polyphasic MUAPs: As surviving nerves branch out to reinnervate orphaned muscle fibers, the resulting motor unit becomes larger and more complex. The machine records this as Motor Unit Action Potentials (MUAPs) that are abnormally large in amplitude, long in duration, and jagged (polyphasic).
- Muscle Distribution: Similar to NCS, EMG changes follow a distal-to-proximal gradient. Abnormalities are first seen in the intrinsic muscles of the foot, followed by distal leg muscles (like the tibialis anterior and gastrocnemius), before eventually reaching the thighs or upper limbs.

Advanced Imaging:

While traditional electrophysiology effectively evaluates large-fiber dysfunction, it lacks the sensitivity to detect the early small-fiber damage characteristic of incipient diabetic neuropathy, necessitating the use of advanced micro-structural imaging modalities. Skin biopsy with immunostaining for protein gene product 9.5 (PGP 9.5) serves as the current gold standard for definitively diagnosing small fiber neuropathy. This technique allows pathologists to physically quantify intraepidermal nerve fiber density (IENFD) and observe the classic length-dependent axonal loss and morphological aberrations, such as axonal swelling, primarily at the distal extremities. Concurrently, Corneal Confocal Microscopy (CCM) has emerged as a revolutionary, non-invasive ophthalmic imaging technique that acts as a reliable window into systemic small fiber health. By optically sectioning the densely innervated cornea, CCM provides rapid, high-resolution quantification of corneal nerve fiber density, branching, and length. Together, these advanced diagnostic tools not only facilitate the detection of small-fiber degradation long before clinical symptoms or large-fiber abnormalities manifest, but they also provide objective, highly sensitive biomarkers essential for monitoring disease progression and evaluating the efficacy of emerging neuroregenerative therapies in clinical trials.

7. Therapeutic Management

The therapeutic management of diabetic peripheral neuropathy (DPN) requires a multifaceted approach, shifting from halting structural disease progression to mitigating debilitating symptoms and preventing downstream complications.

The clinical paradigm encompasses metabolic optimization, pharmacological pain modulation, stringent lifestyle adjustments, and the exploration of disease-modifying agents.

Glycemic Control: The Foundation of Prevention The cornerstone of managing DPN is the rigorous optimization of glycemic control. Stabilization of HbA1c levels is paramount for preventing the onset and halting the progression of neural degradation. Clinical evidence demonstrates that intensive glycemic management significantly reduces the incidence of DPN in patients with type 1 diabetes. While the protective effect is somewhat less absolute in type 2 diabetes—due to compounding factors like dyslipidemia and insulin resistance—sustained euglycemia remains critical. By minimizing extreme glycemic variability, clinicians can reduce the formation of neurotoxic advanced glycation end-products (AGEs) and limit reactive oxygen species, thereby preserving the structural integrity of both the vasa nervorum (blood vessels supplying the nerves) and the nerve axons themselves.Pharmacological Pain ManagementBecause structural neuroregeneration is a protracted process, alleviating the severe, burning, and hyperalgesic symptoms of DPN is a primary clinical imperative. Management relies on neuromodulating agents rather than traditional analgesics. First-line oral therapies include:Gabapentinoids (Pregabalin and Gabapentin): These agents bind to the alpha-2-delta subunit of voltage-gated calcium channels in the central nervous system, effectively dampening the hyper-excitable release of excitatory neurotransmitters like glutamate.SNRIs (Duloxetine and Venlafaxine): Serotonin-norepinephrine reuptake inhibitors enhance the brain's endogenous descending inhibitory pain pathways, altering the perception of nociceptive signals.Topical Treatments: For localized symptomatic relief without systemic side effects, topical 8% capsaicin patches (which deplete substance P from local sensory nerve endings) and 5% lidocaine plasters are highly effective adjuncts.Lifestyle Interventions and Patient EducationNon-pharmacological strategies are essential for holistic DPN management. Dietary modifications aimed at weight reduction and lipid management directly combat the metabolic syndrome components that drive peripheral nerve ischemia. Additionally, specialized, low-impact aerobic and resistance exercise regimens have been shown to improve microvascular endothelial function, enhancing oxygen delivery to starving peripheral nerves. Equally critical is rigorous patient education regarding daily foot care. Because sensory loss removes the protective perception of pain, patients must be trained in daily visual foot inspections, the use of custom-molded pressure-offloading footwear, and regular podiatric maintenance. This prevents the devastating cascade of unnoticed micro-trauma, neuropathic ulceration, and lower extremity amputation.Emerging Therapeutics: Towards Disease ModificationWhile current mainstays are largely palliative, the next frontier in DPN management involves therapies that target foundational pathophysiological mechanisms.Aldose Reductase Inhibitors (ARIs): Drugs such as epalrestat aim to block the first rate-limiting enzyme in the polyol pathway. By preventing the intracellular conversion of excess glucose into sorbitol, ARIs mitigate the osmotic stress and oxidative damage that destroy Schwann cells and axons.Nerve Growth Factors (NGFs): Exogenous neurotrophic factors are under intense investigation for their potential to actively stimulate axonal sprouting and restore small C-fiber integrity, representing a critical shift from mere symptom management to active neuro-restoration.

Emerging Therapeutic Strategies: Treatment options that show promise include reducing brain insulin resistance and focusing on glucocorticoid metabolism. In animal models, interventions like 11β-HSD1 inhibitors and intranasal insulin administration (which overcomes the blood-brain barrier) have shown promise in reducing hippocampus atrophy and restoring cognitive function. In the end, the interaction of brain health, the HPA axis, and metabolic dysregulation highlights the critical need for focused treatment approaches. The medical community can create more efficient, all-encompassing management procedures to safeguard brain health in diabetic patients throughout their lives by expanding our knowledge of the precise molecular mechanisms that connect diabetes and cognitive impairment.

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Correlation Between Diabetes Mellitus And Cardiovascular Disease

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Abstract: Diabetes is a chronic metabolic disorder, raises the risk of cardiovascular diseases and their associated complications. Globally, cardiovascular diseases remain one of the major causes of death and are the most common causes of mortality among individuals with diabetes. In developed countries, heart failure is reported as one of the most frequent causes of death in diabetic patients. According to the World Health Organization (WHO), in 2021 approximately 11% of cardiovascular deaths were attributed to elevated blood glucose levels. The development and progression of cardiovascular diseases in diabetes mellitus are closely associated with several pathological mechanisms, including increased oxidative stress, hypercoagulability, endothelial dysfunction, and autonomic neuropathy. One of the most important forms of cardiovascular diseases in diabetic patients is atherosclerotic cardiovascular disease (ASCVD), which develops through the formation of atherosclerotic plaques within blood vessels. This process is largely driven by insulin resistance and persistent hyperglycaemia. In individuals with diabetes, prediabetes, and obesity, insulin resistance accelerates the progression of atherosclerosis by increasing vascular inflammation, diabetic dyslipidaemia, arterial stiffness, and hypertension.

Key words: Diabetes mellitus, metabolic syndrome, cardiovascular disease, insulin resistance, atherosclerosis, dyslipidaemia, hypertension, dietary management

EXPLANATION OF TERMS

Diabetes Mellitus

Diabetes mellitus is a chronic metabolic condition defined by the body's inability to utilize glucose either completely or partially. It is primarily marked by elevated blood glucose levels and disruptions in the metabolism of carbohydrates, proteins, and lipids. This condition may arise due to defects in the production, secretion, or action of insulin. Insulin is synthesized by the beta cells of the Islets of Langerhans in the pancreas, and a reduction in the number of functional beta cells leads to decreased insulin synthesis and secretion. Prolonged hyperglycaemia is associated with progressive damage to various organs and systems of the body, particularly the cardiovascular system, blood vessels, eyes, kidneys, and peripheral nerves.

Prediabetes

Prediabetes is an intermediate state of abnormal glucose homeostasis in which blood glucose levels are greater than normal but below the diagnostic threshold for diabetes mellitus. It is defined by impaired fasting glucose (IFG) and/or impaired glucose tolerance (IGT) and indicates an enhanced risk of developing type 2 diabetes and cardiovascular disease. The International Diabetes Federation (IDF) reported that the worldwide prevalence of impaired glucose tolerance (IGT) was 12.0%, while the prevalence of impaired fasting glucose (IFG) was 9.2%.

Insulin resistance

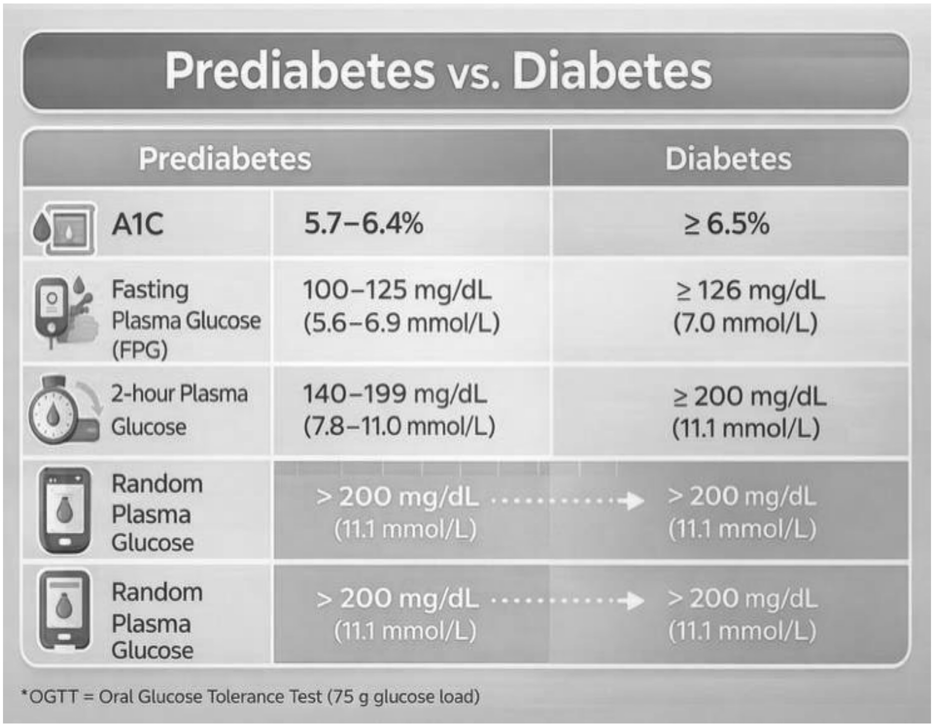
A decreased biological reaction of bodily tissues, including the liver, skeletal muscles, and adipose tissue, to the action of insulin is known as insulin resistance. As a result, glucose uptake and utilization are impaired, leading to increased insulin secretion by pancreatic beta cells and subsequent hyperinsulinemia. This condition can contribute to several metabolic abnormalities, including hyperglycaemia, hypertension, dyslipidaemia, elevated uric acid levels, increased inflammatory markers, endothelial dysfunction, and a prothrombotic state. The most common major outcome associated with insulin resistance is the development of type 2 diabetes mellitus.

Prevalence of Diabetes Mellitus

According to the International Diabetes Federation (IDF), diabetes continues to represent a significant global health burden. In 2024, approximately 589 million adults were living with diabetes worldwide and around 1.1 billion adults were reported to have impaired glucose tolerance or impaired fasting glycaemia. According to the India Science, Technology and

Innovation Portal, prevalence of diabetes in India has shown a substantial and continuous increase over the past decades. In the year 2000, the estimated number of individuals living with diabetes was approximately 32 million. This figure rose to 41 million in 2007, followed by a significant increase to 62 million in 2011. By 2017, the number had further escalated to 73 million cases. Projections indicate that this burden is likely to rise considerably, reaching approximately 134 million by the year 2045. The global prevalence of diabetes and the number of untreated cases have shown a consistent upward trend over recent decades, highlighting the urgent need for strengthened healthcare interventions and public health strategies.

Diagnostic criteria for prediabetes and diabetes mellitus according to the American Diabetes Association



Prediabetes vs. Diabetes

	Prediabetes	Diabetes
A1C	5.7–6.4%	≥ 6.5%
Fasting Plasma Glucose (FPG)	100–125 mg/dL (5.6–6.9 mmol/L)	≥ 126 mg/dL (7.0 mmol/L)
2-hour Plasma Glucose	140–199 mg/dL (7.8–11.0 mmol/L)	≥ 200 mg/dL (11.1 mmol/L)
Random Plasma Glucose	> 200 mg/dL (11.1 mmol/L) →	> 200 mg/dL (11.1 mmol/L)
Random Plasma Glucose	> 200 mg/dL (11.1 mmol/L) →	> 200 mg/dL (11.1 mmol/L)

*OGTT = Oral Glucose Tolerance Test (75 g glucose load)

Source: Reprinted from https://www.ncbi.nlm.nih.gov/sites/books/NBK378977/figure/diab-transplant.F1/

Classification of Diabetes Mellitus

Type-1 diabetes (T1DM)

T1DM, commonly referred to as juvenile-onset diabetes or insulin-dependent diabetes mellitus (IDDM), usually has a sudden onset and is most commonly seen in the younger age group, especially in children and adolescents. Type 1 diabetes accounts for approximately 5–10% of all diagnosed cases of diabetes mellitus. Type 1 diabetes is further classified into two forms-

- Immune-mediated type – caused by autoimmune destruction of beta cells, causing little or no insulin production and resulting in hyperglycaemia. Patients require daily insulin therapy, and ketoacidosis is common. A slowly progressive form in adults is known as latent autoimmune diabetes (LADA).
- Idiopathic type – No definite cause or aetiology is identified .

Risk factors for T1DM

Genetic predisposition- Type-1 diabetes has a strong genetic basis and is recognized as a polygenic disorder. A considerable proportion of its heritability is attributed to HLA class II genes located on chromosome 6.

Viral infections- Certain viral infections, such as Coxsackie virus, may trigger an autoimmune response against the pancreatic beta cells, leading to impaired insulin secretion and eventual cell destruction.

Acute stress- Severe physical or emotional stress can increase the release of counter-regulatory hormones such as adrenaline, noradrenaline, and cortisol, which raise blood glucose levels.

Physical injury or surgery- Trauma, major surgery or significant emotional distress may act as triggering factors by increasing catabolic hormone secretion and disrupting glucose homeostasis.

Immunological factors- Type-1 diabetes is an autoimmune disease in which the immune system gradually destroys insulin-producing beta cells in the pancreas. Clinical symptoms usually appear after a substantial loss of these cells.

Family history- A family history of type-1 diabetes, particularly in a parent or sibling, increases the risk of developing the condition.

Type-2 diabetes mellitus (T2DM)

T2DM also referred as adult-onset diabetes or non-insulin-dependent diabetes mellitus (NIDDM), is the most common form of diabetes, accounting for approximately 90–95% of all diagnosed cases worldwide. It is characterized by insulin resistance, followed by progressive beta-cell dysfunction, which eventually leads to inadequate insulin production and hyperglycaemia. T2DM commonly occurs in middle-aged and older adults, especially after the age of 40 years, although it is increasingly being observed in younger individuals due to rising rates of obesity and sedentary lifestyles. Both genetic and environmental factors contribute significantly to the development of this disease. Important risk factors include family history, obesity, physical inactivity, unhealthy diet, advancing age, and having multiple pregnancies. As the disease progresses, many patients may eventually require exogenous insulin therapy to maintain adequate glycaemic control.

Management often includes weight reduction, dietary modification, physical activity, oral hypoglycaemic agents, and insulin therapy when necessary.

Risk factors for T2DM

Genetic predisposition- Type-2 diabetes has a strong hereditary component. Individuals with a family history of diabetes or belonging to high-risk ethnic groups, including South Asian populations, have an increased risk of developing the condition.

Obesity and overweight- Excess body weight, particularly central or abdominal obesity, is a major risk factor. Increased adipose tissue contributes to insulin resistance, which is a key underlying mechanism in type-2 diabetes.

Abdominal fat distribution- A high waist-hip ratio indicates increased visceral fat accumulation, which is strongly associated with insulin resistance and a greater risk of diabetes.

Sedentary lifestyle- Physical inactivity reduces insulin sensitivity and promotes weight gain, significantly increasing the likelihood of developing type-2 diabetes.

Unhealthy dietary habits- Diets high in refined carbohydrates, high glycaemic index foods, saturated fats, trans fats, and excess calories increase the risk. Low intake of dietary fibre, micronutrients, and antioxidants may increase the risk of T2DM.

Age- T2DM is more common in middle-aged and older adults, with the risk increasing significantly after 45 years of age.

Metabolic syndrome- T2DM is often associated with hypertension, dyslipidaemia, and obesity, collectively referred to as metabolic syndrome (syndrome X).

Impaired beta-cell function- Along with insulin resistance, reduced pancreatic beta-cell function contributes to inadequate insulin secretion.

Excess alcohol consumption- Excessive alcohol consumption may contribute to poor glucose regulation and increase diabetes risk.

Gestational diabetes mellitus

Gestational diabetes mellitus can develop at any time during pregnancy, most commonly in the second or third trimester and usually disappears after delivery. However, women who develop this condition have a higher risk of developing type 2 diabetes later in life. Major risk factors include previous gestational diabetes, delivery of a macrosomia baby, overweight or obese, maternal age, having a family history of type 2 diabetes mellitus and polycystic ovary syndrome (PCOS).

Type of Other Specific Diabetes Mellitus

Type	**Cause / Mechanism**	**Examples**
Diabetes due to diseases of the pancreas	Damage to pancreatic beta cells leading to reduced insulin production	Pancreatitis, pancreatic trauma, pancreatic infections, pancreatic cancer, pancreatectomy
Diabetes due to endocrine disorders	Excess secretion of hormones that oppose insulin action	Cushing’s syndrome, acromegaly, hyperthyroidism
Drug- or chemical-induced diabetes	Medications or chemicals interfere with insulin secretion or insulin action	Corticosteroids, thiazide diuretics, certain antipsychotic drugs
Infection-related diabetes	Viral infections cause beta-cell destruction	Congenital rubella, cytomegalovirus (CMV) infection
Diabetes associated with genetic syndromes	Genetic abnormalities linked with impaired glucose metabolism	Prader–Willi syndrome, Down syndrome, Friedreich’s ataxia
Malnutrition-related diabetes mellitus	Severe nutritional deficiency affects pancreatic function and glucose metabolism	Severe malnutrition / protein-energy deficiency

Symptoms of Diabetes Mellitus

Hyperglycaemia- Elevated blood glucose due to insufficient insulin production or impaired insulin action.

Glycosuria- Presence of glucose in urine when blood glucose exceeds the renal threshold (~180 mg/dL).

Polyuria- Excessive urination caused by osmotic diuresis.

Nocturia- Frequent urination during the night.

Polydipsia- Excessive thirst due to fluid loss and dehydration.

Polyphagia- Increased hunger caused by reduced glucose utilization by body tissues.

Dehydration- Loss of water and electrolytes resulting from persistent polyuria.

Fatigue and weakness- Reduced cellular glucose uptake leading to low energy levels.

Electrolyte imbalance- Increased urinary loss of sodium, potassium, magnesium, and phosphorus.

Ketoacidosis- Accumulation of ketone bodies causing metabolic acidosis, especially in severe insulin deficiency.

Fruity breath odour- due to acetone exhalation in diabetic ketoacidosis.

Blurred vision- Due to osmotic changes in the lens and retinal damage.

Delayed wound healing- Poor circulation and high blood glucose impair tissue repair.

Recurrent infections- Increased susceptibility to bacterial and fungal infections, especially Candida.

Neuropathy symptoms- Numbness, tingling, or pain in the limbs in chronic cases.

Cardiovascular Disease (CVD)

The term CVD describes to a group of conditions that affect the heart and blood vessels, including arteries and veins. It remains the leading cause of death worldwide. According to World Health Organization (WHO), approximately 19.8 million people died from CVDs in 2022, accounting for nearly 32% of all deaths globally. Among these deaths, around 85% were attributed to heart attack and stroke. Most cardiovascular diseases are largely preventable through the management of behavioural and environmental risk factors. Early detection and timely intervention are essential to reduce complications. Appropriate screening, counselling, lifestyle modification, and pharmacological treatment can significantly improve outcomes and reduce mortality due to CVD.

Prevalence of Cardiovascular Diseases

CVD remains the leading cause of death in many countries worldwide. However, in most cases, it is highly predictable, preventable, and treatable. In India, CVD tends to occur at a younger age, presents with greater severity, and progresses more rapidly and aggressively.

Prevalence in India

INDIA	
Overall number of deaths from CVD (2021):	2,873,266
Crude CVD mortality (per 100,000 population) (2021):	203
Age-standardized CVD mortality (per 100,000 population) (2021):	268
Age-standardized CVD incidence (per 100,000 population) (2021):	905
Prevalence of hypertension (women) (2019):	30.5%
Prevalence of hypertension (men) (2019):	31.6%

Source: https://world-heart-federation.org/world-heart-observatory/countries/india/

Types of Cardiovascular Diseases (CVDs)

Coronary heart disease (CHD)- narrowing of the blood vessels that supply the heart muscle

Heart attack (myocardial infarction)- blockage of blood flow to the heart, causing damage to the heart muscle

Cerebrovascular disease- diseases affecting blood vessels of the brain

Heart failure- inability of the heart to pump blood effectively

Arrhythmia- abnormal or irregular heartbeat

Cardiomyopathy- diseases of the heart muscle

Heart valve disease- disorders affecting heart valves

Aortic disease- widening or tearing of the aorta

Pericardial disease- inflammation of the sac surrounding the heart

Vascular disease- disorders affecting the circulatory system

Risk Factors for CVD

The risk factors for cardiovascular disease can be organized into four broad groups based on their effect and the possibility of modification.

Group I: Established modifiable factors	**Group II: Probable modifiable factors**	**Group III: Emerging associated factors**	**Group IV: Non-modifiable factors**
Smoking	Diabetes mellitus	Psychological stress	Increasing age
Elevated LDL cholesterol	Lack of physical activity	Lipoprotein (a)	Male sex
Diet rich in saturated fat and cholesterol	Low HDL cholesterol	Raised homocysteine	Family history of premature CVD
High blood pressure	High triglycerides and small dense LDL	Oxidative stress	
Left ventricular hypertrophy	Excess body weight / obesity	Abstinence from alcohol	
Increased thrombogenic tendency	Postmenopausal status		

Source: Adapted from (Srilakshmi, 2024, p. 323)

Saturated Fat

Saturated fats are dietary fats mainly found in animal-based foods such as meat, butter, full-fat dairy products, and in tropical oils like coconut and palm oil. They are usually solid at room temperature and excessive intake may increase cardiovascular risk.

Cholesterol

Cholesterol is a waxy, fat-like substance that the body needs to build cells and produce hormones. Although the liver makes all the cholesterol required by the body, excess cholesterol in the blood, particularly LDL cholesterol, increases the risk of heart disease and stroke.

Trans Fatty Acids (TFAs)

Trans fatty acids are a type of unsaturated fat formed mainly during the industrial partial hydrogenation of vegetable oils to produce solid fats. High intake of trans fats is strongly associated with an increased risk of cardiovascular disease.

Triglycerides

Triglycerides are the most common type of fat (lipid) in the blood and body. They are derived from dietary fats and from excess calories that are stored in fat cells for later energy use. Elevated triglyceride levels can increase the risk of heart disease, stroke and metabolic syndrome.

Desirable Cholesterol and Triglycerides Level

Parameter	**Level (mg/dL)**	**Interpretation**
Total Cholesterol	< 160	Desirable level
	160-199	Normal risk
	200–240	Borderline
	> 240	High risk
HDL Cholesterol	> 55	Desirable level
	35-55	Borderline

Parameter	Level (mg/dL)	Interpretation
	<35	High risk
Triglycerides	< 150	Desirable level
	150–199	Borderline
	200–400	Normal risk
	> 400	High risk

Source: Adapted from (Srilakshmi, 2024, p. 323)

Common Symptoms of Cardiovascular Diseases (CVDs)

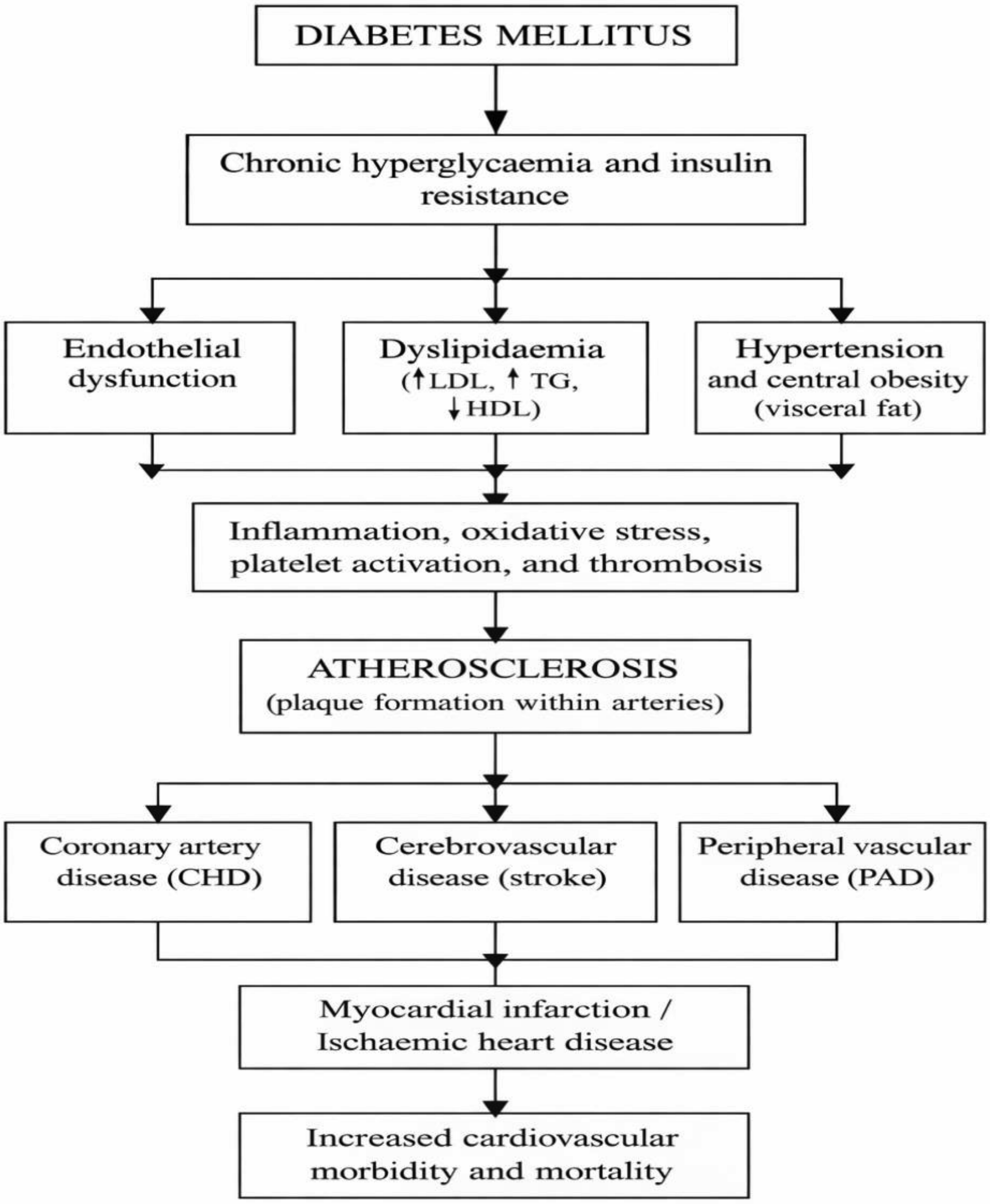
- Chest pain, pressure, tightness or discomfort, especially in the centre of the chest
- Pain or discomfort spreading to the left arm, shoulder, neck, jaw, elbows or back
- Shortness of breath or difficulty breathing
- Fatigue or weakness, especially during physical activity
- Dizziness, light-headedness
- Palpitations or irregular heartbeat
- Very fast or very slow heart rate
- Cold sweats and pale skin
- Nausea or vomiting
- Swelling of the hands, legs, ankles or feet
- Pain, weakness, or numbness in the arms or legs
- Persistent dry cough, particularly in heart failure
- Fever, skin rashes or unusual spots in some heart-related inflammatory conditions
- Stroke- Sudden weakness or numbness of the face, arm or leg (usually on one side of the body), difficulty speaking or understanding speech, confusion, vision problems in one or

both eyes, dizziness, loss of balance, difficulty walking, severe sudden headache, fainting or unconsciousness.

- Heart Attack- Intense chest pain or pressure, pain radiating to the left arm or jaw, difficulty breathing.

RELATIONSHIP BETWEEN DIABETES MELLITUS AND CARDIOVASCULAR DISEASE

Diabetes mellitus is strongly associated with cardiovascular disease (CVD). Individuals with diabetes have a markedly increased risk of cardiovascular disease, with evidence indicating that their chance of developing heart disease is nearly three to four times higher than that of non-diabetic individuals. The association between diabetes and heart disease is primarily mediated through several metabolic abnormalities, including insulin resistance, dyslipidaemia, hypertension, and central obesity. These factors are often present together as part of the metabolic syndrome, which significantly increases the risk of both diabetes mellitus and cardiovascular disease. Chronic hyperglycaemia and elevated insulin levels contribute to endothelial dysfunction by damaging the inner lining of blood vessels, thereby promoting the formation of atherosclerotic plaques within coronary arteries. In addition, diabetes is commonly associated with lipid abnormalities such as elevated triglycerides, increased low-density lipoprotein (LDL) and reduced high-density lipoprotein (HDL), all of which enhance atherogenesis. Diabetes also increases platelet adhesiveness and blood clotting tendency, raising the risk of thrombosis, myocardial infarction and stroke. As a result, macrovascular complications are the leading cause of death in diabetic patients, accounting for nearly 80% of total mortality. Therefore, maintaining strict glycaemic control, managing postprandial glucose levels and controlling associated risk factors such as hypertension, obesity and dyslipidaemia are essential in reducing cardiovascular morbidity and mortality in individuals with diabetes mellitus.



Dietary Guidelines for the Management of Patients with Cardiovascular Disease (CVD) and Diabetes Mellitus (DM)

Dietary management plays a central role in controlling blood glucose levels, improving lipid profile, maintaining healthy body weight, and reducing cardiovascular risk in patients with diabetes mellitus.

- Maintain an ideal body weight through calorie-controlled meals and regular physical activity. In overweight or obese individuals, even modest weight loss can improve glycaemic control, blood pressure and serum lipids.
- Distribute total calorie intake evenly throughout the day by consuming three main meals with healthy snacks in between to prevent hypoglycaemia and large postprandial glucose fluctuations.
- Prefer complex carbohydrates and high-fibre foods such as whole grains, millets, legumes, oats and sprouts. Refined cereals, polished rice and simple sugars should be avoided.
- Increase dietary fibre intake through fruits, vegetables, green leafy vegetables, whole grains and pulses, as fibre helps improve glucose control and reduce cholesterol levels.
- Choose low glycaemic index (GI) foods to minimize rapid rises in blood glucose levels.
- Limit saturated fats and avoid trans fats by reducing intake of fried foods, bakery products, processed foods, red meat, butter, ghee and hydrogenated fats.
- Use healthy fats in moderation, especially monounsaturated and polyunsaturated fats.
- Include lean protein sources such as fish, skinless chicken, legumes, pulses, beans and low-fat dairy products.
- Consumption of fish, especially fatty fish rich in omega-3 fatty acids, as it helps reduce cardiovascular risk.
- Restrict dietary cholesterol intake by limiting egg yolk, organ meats, red meat, and high-fat animal products.
- Increase fruits and vegetables to at least five servings per day to ensure adequate antioxidants, vitamins, minerals, and fibre.
- Limit sodium intake, especially in hypertensive patients, to help control blood pressure.
- Avoid sugary drinks, sweets, pastries, cakes, chocolates, and sweetened beverages, as these contribute to poor glycaemic control and excess calorie intake.
- Restrict alcohol consumption and avoid smoking, as both increase cardiovascular risk.

- Maintain adequate hydration and include sufficient water intake daily.
- Adopt evidence-based dietary patterns, such as the Mediterranean diet, DASH diet, vegetarian, or plant-based diets, which improve cardiovascular health.

World Diabetes Day- 14th November

World Heart Day- 30th September

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Diabetes and Liver disorders

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PART I:- DIABETES MELLITUS

INTRODUCTION

Diabetes mellitus is an intricate metabolic disease defined as chronic hyperglycemia due to inadequate insulin secretion, insulin action, or both (Patil et al., 2023). It encompasses metabolic disorders stemming from insufficient insulin production, causing high blood sugar (Galicia-Garcia et al., 2020), and represents a major global public health challenge with escalating prevalence, morbidity, mortality, and economic burden (Patil et al., 2023).

EPIDEMIOLOGY

T1DM incidence rose 2.01/10,000 (males) and 1.70/10,000 (females) from 1990–2019, while mortality declined (Li et al., 2021). T2DM incidence increased 0.81%/year (males) and 0.37%/year (females), with decreasing male mortality (Li et al., 2021). GDM rose to 101.8 per 1,000 deliveries and T2DM in pregnancy to 6.4 per 1,000 (Ngwezi et al., 2023), underscoring the need for stronger prevention strategies.

PATHOPHYSIOLOGY

Insulin secretion is regulated by glucokinase, ATP-sensitive potassium channels, and incretin hormones (Seino et al., 2010; Vybhavi et al., 2025). In T1DM, T- and B-cells destroy β-cells (Craig et al., 2009); in T2DM, β-cell failure results from glucotoxicity, lipotoxicity, oxidative stress, ER stress, and inflammation (Moon et al., 2020; Vybhavi et al., 2025), activating the polyol, hexosamine, PKC, and AGE pathways (Yki-Jarvinen, 1992). Insulin resistance in muscle, liver, and fat (Galicia-Garcia et al., 2020; Ruze et al., 2023) is driven by visceral fat-induced TNF-α and IL-6, reducing insulin signaling and stimulating hepatic gluconeogenesis

(Hotamishligil et al., 1995). Additional mechanisms include ROS overproduction and NADPH imbalance (Ohiagu et al., 2021; Iheagwam et al., 2025; Moon, 2023). Gut dysbiosis further promotes metabolic dysfunction and systemic inflammation (Tunuguntla, 2024), while macrophage and neutrophil activation sustain β-cell destruction and meta-inflammation (Giovenzana et al., 2021; Sur and Banu, 2022).

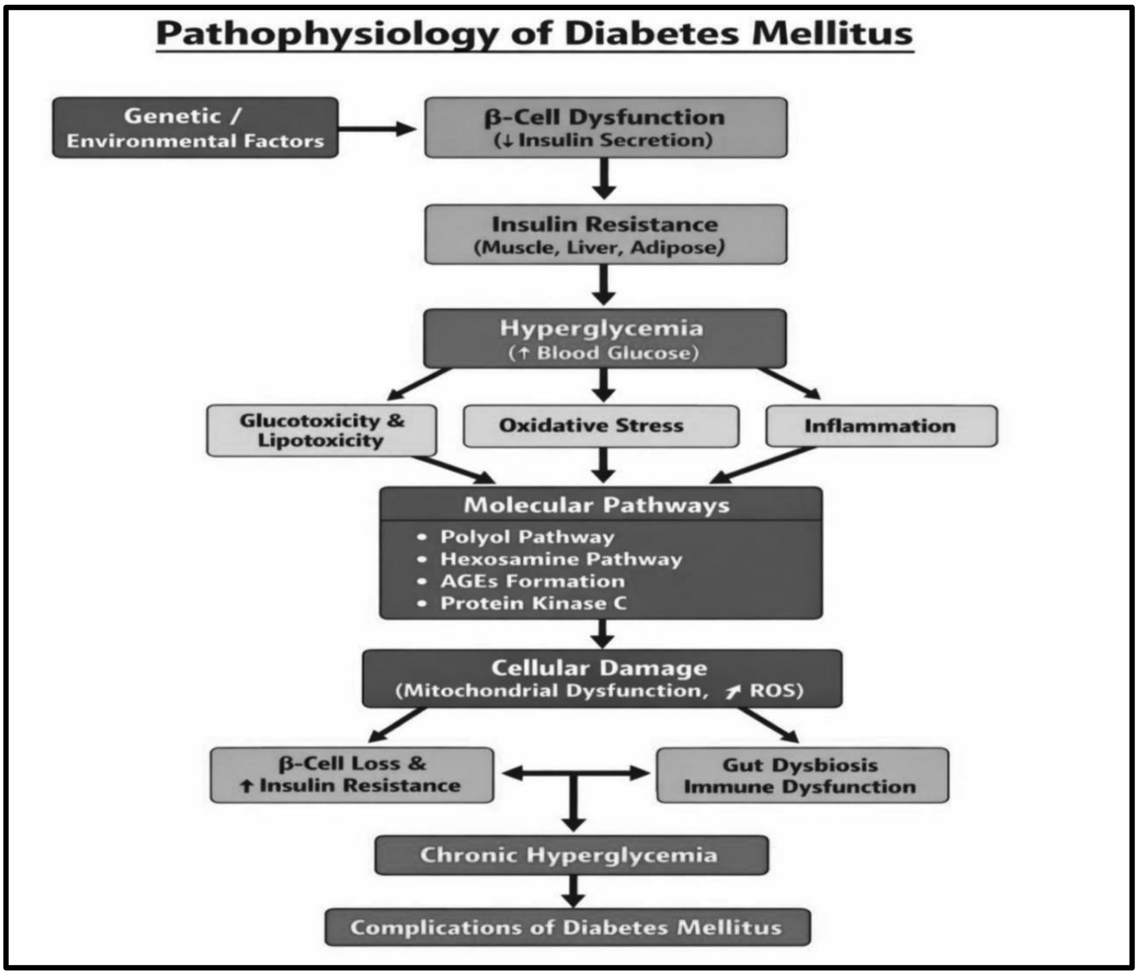

Figure 1: Diabetes Mellitus Pathophysiology

CLASSIFICATION OF DIABETES MELLITUS

Diabetes mellitus encompasses numerous aetiological and pathophysiological types, each with distinct clinical manifestations and treatment implications (Seino et al., 2010).

Type 1 Diabetes Mellitus

T1DM (IDDM/juvenile diabetes) accounts for ~5% of diabetes globally, resulting from autoimmune β-cell destruction driven by genetic predisposition and environmental triggers

(Jeremiah et al., 2024). It requires lifelong insulin administration (Patil et al., 2023). Clinical features include polyuria, polydipsia, weight loss, fatigue, and risk of diabetic ketoacidosis, with serological markers such as islet cell, GAD, and tyrosine phosphatase antibodies (Craig et al., 2009).

Type 2 Diabetes Mellitus

T2DM, the most prevalent form, involves insulin resistance and progressive β-cell dysfunction, influenced by obesity, sedentary lifestyle, and ageing (Jeremiah et al., 2024; Vybhavi et al., 2025). It is closely associated with metabolic syndrome (Rosenbloom et al., 2009) and often asymptomatic early (Patil et al., 2023). Management progresses from lifestyle modification and oral antidiabetics to insulin therapy as needed (Rosenbloom et al., 2009).

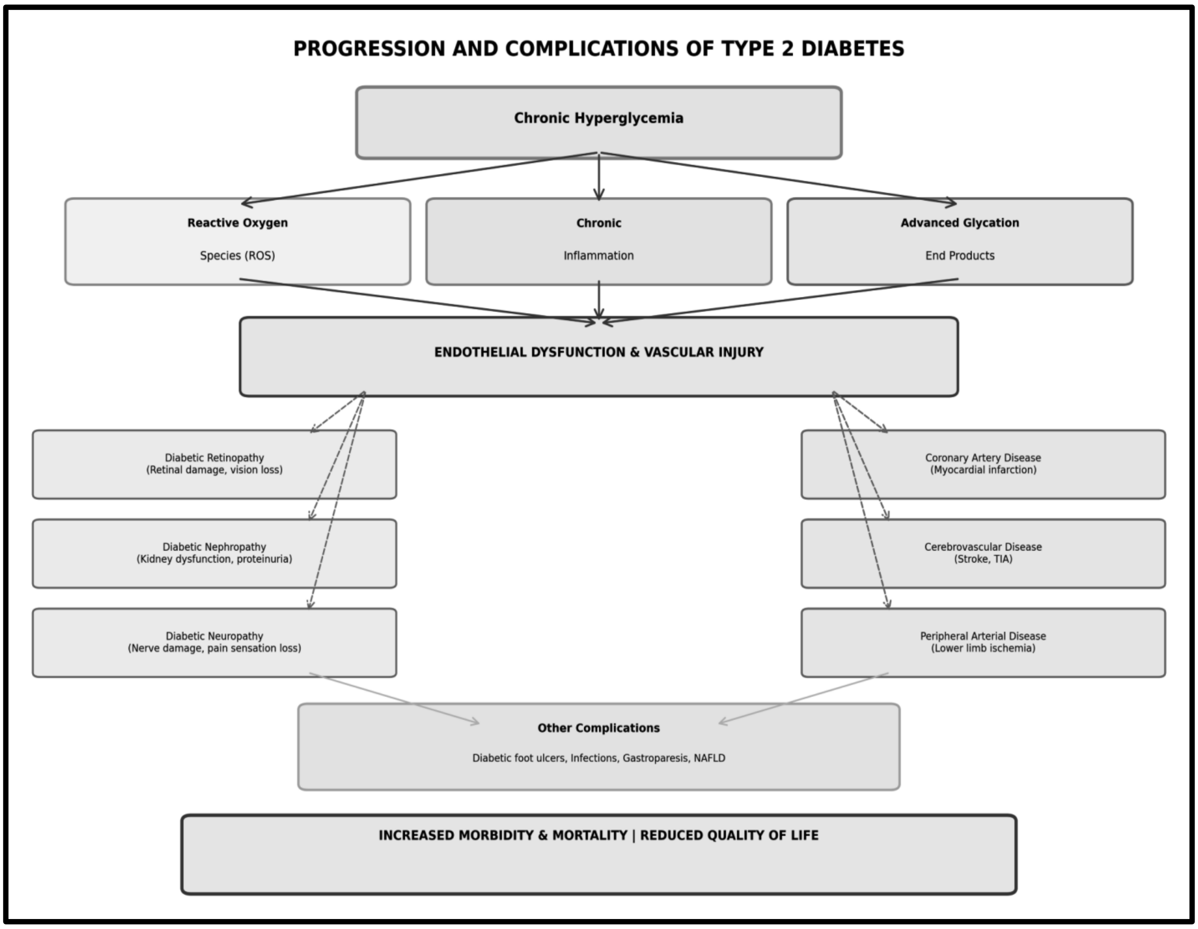

Figure 2: Progression and Complications of Type 2 Diabetes - Demonstrating the cascade from chronic hyperglycemia through vascular damage to clinical complications

Secondary Diabetes Mellitus

Secondary diabetes arises from underlying conditions causing detectable hyperglycemia. Type 3c diabetes, comprising 15–20% of cases in Southeast Asia and India, stems from pancreatic pathology involving inflammation, insulin-incretin axis dysfunction, β-cell destruction, and genetic effects (Fadieienko et al., 2024). Endocrinopathies causing hormonal dysregulation further impair β-cell function and insulin sensitivity (Popoviciu et al., 2023). Additional causes include chronic pancreatitis with exocrine insufficiency (Bahl et al., 2023) and viral infections such as hepatitis C and coxsackie B in predisposed individuals (Jeremiah et al., 2024).

SYMPTOMATIC PRESENTATION

Symptom	Description
Glucosuria	Blood glucose exceeds renal threshold (180 mg/dl); excreted in urine, causing osmotic effects
Polyuria	Excess urine output from osmotic diuresis due to hyperglycemia
Polydipsia	Excessive thirst from dehydration and hypothalamic thirst center stimulation
Polyphagia	Increased appetite and overeating due to cellular glucose starvation
Asthenia	Insulin deficiency reduces protein synthesis; increases breakdown causing weakness
Ketoacidosis	Excessive fat metabolism generates ketoacids, leading to metabolic acidosis
Acetone Breath	Fruity odour from acetone release; signals life-threatening ketoacidosis
Kussmaul Breathing	Deep, rapid respirations compensating for severe metabolic acidosis

Osmotic Diuresis	Marked dehydration progressing to circulatory shock, metabolic derangements, and coma (Sembulingam et al., 2012)

COMPLICATIONS

Category	Complication	Key Features
Microvascular	Diabetic Retinopathy	Microaneurysms → neovascularisation → vision loss (Hauwanga et al., 2024; Chandan, 2023)
	Nephropathy	Glomerular damage → microalbuminuria → proteinuria → renal failure
	Neuropathy	Nerve damage; burning, tingling, numbness; autonomic dysfunction (Nascimento et al., 2016)
Macrovascular	Coronary Artery Disease	2–4× myocardial infarction risk; often silent (Artime et al., 2021)
	Cerebrovascular Disease	Elevated stroke risk with severe consequences
	Peripheral Arterial Disease	Claudication → ulcers → amputation (Aboelmaaty et al., 2025)
Other	Diabetic Foot Ulcers	Neuropathy + poor circulation → infection → amputation (Aboelmaaty et al., 2025)
	Diabetic Cardiomyopathy	Direct myocardial injury → heart failure (Li et al., 2022; Siam et al., 2024)
	Cognitive & Mental Health	Depression, dementia, psychiatric disorders (Chen et al., 2022; Siam et al., 2024)
	Metabolic Memory	Prior hyperglycaemia drives persistent chronic complications (Natarajan, 2021)

PART II:- LIVER DISORDER

INTRODUCTION

Liver disease is a major global public health issue, causing nearly 2 million deaths annually from cirrhosis and associated complications (Jalili et al., 2023). The liver performs critical roles in metabolism, plasma protein synthesis, detoxification, and immune regulation. Chronic liver injury exceeding regenerative capacity leads to progressive fibrosis and cirrhosis — characterised by regenerating nodules and structural distortion — ultimately impairing hepatic function (Gambardella et al., 2025). Disease severity ranges from simple fatty infiltration to decompensated cirrhosis and acute liver failure (Grander et al., 2023).

EPIDEMIOLOGY

Liver disease prevalence has risen substantially over two decades. MASLD/NAFLD affects approximately 25–30% of the global population (Grander et al., 2023), while alcoholic liver disease (ALD) impacts ~8% of the U.S. population. Viral hepatitis remains significant, with ~300 million hepatitis B and 120–150 million hepatitis C infections worldwide (Dang et al., 2019). Cirrhosis mortality ranges from 5–7%/year in compensated disease to 43.8% with decompensating complications (Mohammadi et al., 2025).

PATHOPHYSIOLOGY

Early liver damage and inflammation

Early Injury & Inflammation Hepatocyte injury from viral infections, alcohol, toxins, metabolic dysfunction, or autoimmune disease activates innate immunity (Kupffer cells), releasing inflammatory cytokines TNF-α, IL-6, and IL-1β (Grander et al., 2023).

Oxidative Stress and Lipotoxicity

Excess triglycerides, cholesterol, and free fatty acids overload hepatocytes, generating reactive oxygen species (ROS) that overwhelm antioxidant defences, causing lipid peroxidation, mitochondrial dysfunction, ER stress, and hepatocyte apoptosis or necrosis (Grander et al., 2023).

Fibrogenesis and Hepatic Stellate Cell Activation

Chronic injury activates hepatic stellate cells (HSCs) into collagen-producing myofibroblasts via TGF-β, TNF-α, PDGF, oxidative stress, and endotoxaemia, depositing collagen types I and III and driving progressive fibrosis (Merwe et al., 2024).

Disrupted Liver Microcirculation and Portal Hypertension

Cirrhotic architectural distortion accounts for ~70% of raised intrahepatic vascular resistance, compounded by reduced nitric oxide and prostacyclin and elevated vasoconstrictors (García–Tsao et al., 2016; Gambardella et al., 2025). Compensatory splanchnic vasodilation activates RAAS, causing sodium retention and hyperdynamic circulation (García–Tsao et al., 2016).

Dysbiosis and Enhanced Intestinal Permeability

Portal hypertension promotes gut dysbiosis and barrier dysfunction, driving bacterial translocation and endotoxaemia, worsening inflammation, fibrogenesis, and endothelial dysfunction (Tranah et al., 2020)

Portal Hypertension Systemic Manifestations

Portal hypertension induces mesenteric congestion, promoting gut dysbiosis and intestinal barrier dysfunction. Increased permeability facilitates bacterial translocation and endotoxaemia, which amplify systemic inflammation, oxidative stress, immune dysfunction, fibrogenesis, and endothelial dysfunction, further perpetuating portal hypertension and cirrhosis-associated immune dysregulation (CAID) in a self-reinforcing pathological cycle (Tranah et al., 2020).

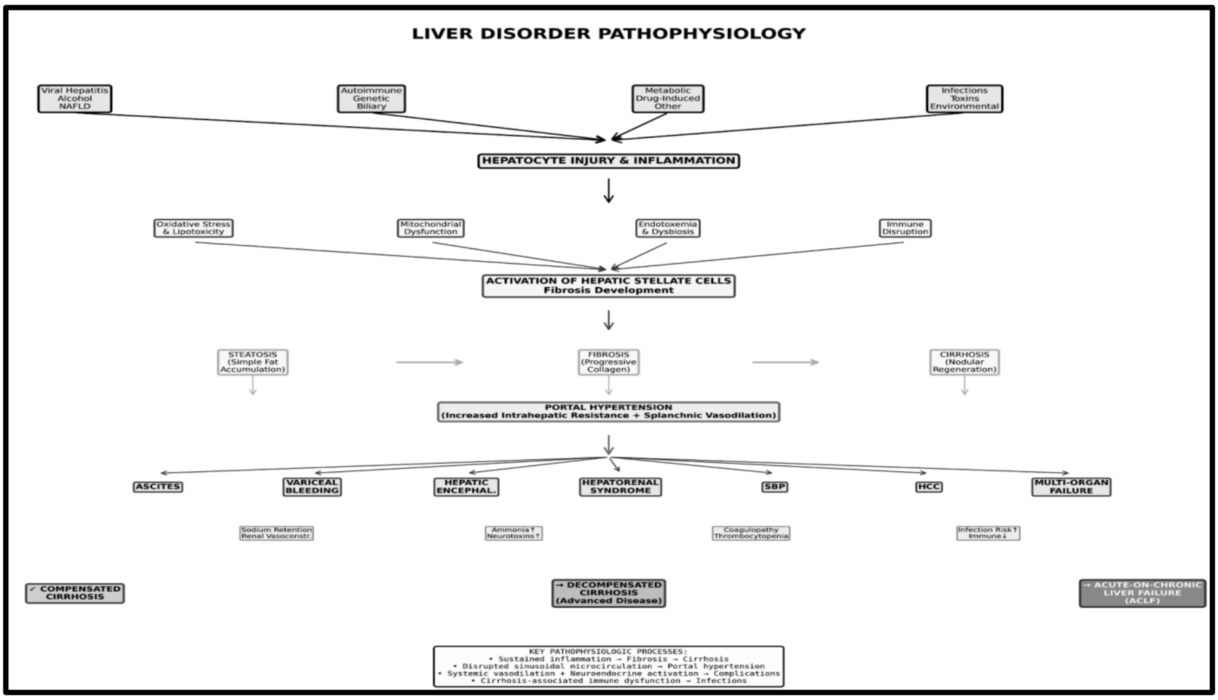

Figure 3: Pathophysiology of liver disorder

CLASSIFICATION

Category	Classification	Key Features
Clinical Stage	Stage 1 – Compensated	No portal hypertension; asymptomatic; normal synthetic function
	Stage 2 – Compensated with Portal Hypertension	HVPG ≥10 mmHg; no decompensation (Gambardella et al., 2025)
	Stage 3 – Decompensated	Variceal haemorrhage
	Stage 4a – Decompensated	Hepatic encephalopathy
	Stage 4b – Decompensated	Ascites formation
	Stage 5 – Decompensated	≥2 simultaneous complications (Mohammadi et al., 2025)
Etiology	Viral	Hepatitis A, B, C, D, E; CMV; EBV
	Alcoholic Liver Disease	Steatosis → hepatitis → cirrhosis (O'Shea et al., 2009)
	MASLD	Obesity, T2DM, insulin resistance, dyslipidaemia (Portincasa & Baffy, 2024)
	Autoimmune Hepatitis	Immune-mediated inflammatory liver disease(Gerven et al., 2016)
	Cholestatic Diseases	PSC and PBC
	Genetic/Metabolic	Hemochromatosis, Wilson disease, α-1 antitrypsin deficiency
	Other	NASH, sepsis-related, drug-induced liver injury

Histological (METAVIR)	F0	No fibrosis
	F1	Portal fibrosis without septa
	F2	Portal fibrosis with few septa
	F3	Multiple septa; non-cirrhotic
	F4	Cirrhosis

SYMPTOMATIC PRESENTATION

Early Disease Presentation

Early liver disease is often asymptomatic, incidentally detected via routine imaging or labs. Constitutional symptoms include fatigue, malaise, and anorexia, alongside mild right upper quadrant discomfort. Lab abnormalities show elevated transaminases — ALT>AST in NAFL ; AST>ALT in alcoholic liver disease (Rosenberg et al., 2023).

Compensated Cirrhosis

Despite significant structural damage, compensated cirrhosis may present subtly with spider angiomas, palmar erythema, caput medusae, hepatomegaly, and splenomegaly. Labs reveal thrombocytopenia, prolonged prothrombin time, and hypoalbuminaemia (Gambardella et al., 2025).

Decompensated Cirrhosis

Decompensation manifests as ascites (SAAG ≥1.1 g/dL) causing abdominal distension and dyspnoea (Baiges et al., 2022); variceal bleeding presenting as haematemesis or melaena, carrying high mortality (García-Tsao et al., 2016); hepatic encephalopathy ranging from confusion to coma per West Haven criteria (Esmail et al., 2025); jaundice from hyperbilirubinaemia; and coagulopathy with elevated INR and bleeding risk (Scharf, 2021)

COMPLICATION

Portal Hypertension

Elevated HVPG (≥10 mmHg) drives increased intrahepatic resistance (García-Tsao et al., 2016), causing ascites via RAAS activation and hypoalbuminaemia (Baiges et al., 2022), and variceal bleeding with 15–25% mortality (García-Tsao et al., 2016). Hepatorenal syndrome causes functional renal failure with high mortality.

Infection-Relate

SBP (commonly *E. coli*) carries high mortality (Mohan et al., 2023). Immune dysfunction elevates pneumonia, UTI, and sepsis risk (Tranah et al., 2020).

HCC

Annual incidence 1–3% in cirrhotic patients (Ferenci et al., 2010); risk factors include viral hepatitis, alcohol, and NASH; early stages are often asymptomatic**.**

Extrahepatic

Complications include cirrhotic cardiomyopathy, hepatopulmonary syndrome (Han et al., 2023), portopulmonary hypertension, osteoporosis with fracture risk (Gorbacheva et al., 2024), and dementia risk particularly in alcohol-related disease (Zhao et al., 2023).

BIDIRECTIONAL RELATIONSHIP BETWEEN LIVER DISORDER AND DIABETES MELITUS

Chronic liver disease (cirrhosis, MASLD) impairs glucose metabolism and insulin clearance, driving insulin resistance and hepatogenous diabetes (Padda et al., 2021). Conversely, diabetes mellitus promotes hepatic fat accumulation, steatohepatitis, fibrosis, and HCC risk through chronic hyperglycaemia and insulin resistance (Williams et al., 2024). Shared mechanisms — inflammation, oxidative stress, lipotoxicity, and gut microbiota dysbiosis — amplify this bidirectional relationship, necessitating integrated metabolic and hepatic management (Takeuchi, 2014; Schmid et al., 2011).

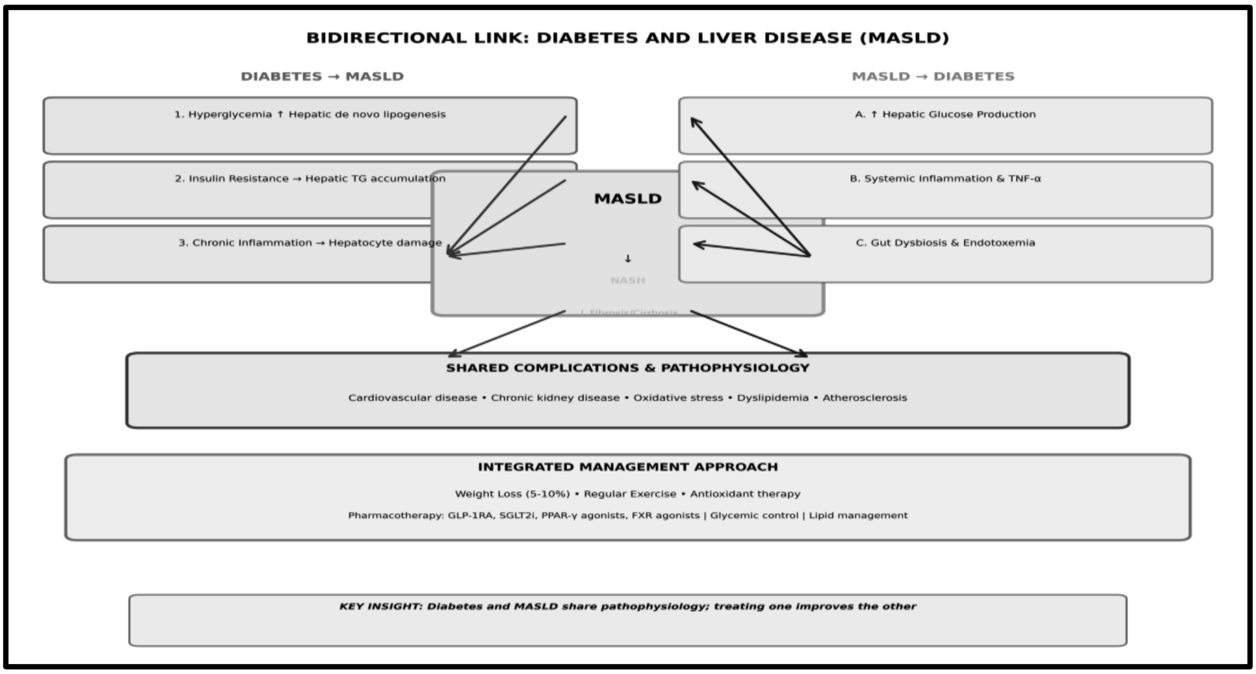

Figure 4: Bidirectional Link Between Diabetes and MASLD

CONCLUSION

Diabetes mellitus and liver diseases are two directly linked metabolic disorders that have common processes including insulin resistance, oxidative stress and inflammation. The two conditions are major causes of morbidity and mortality globally, and diabetes facilitates the advancement of liver diseases and liver dysfunction that further degrade glucose metabolism.

Their comorbidity heightens the chances of serious complications, such as cardiovascular disease, liver failure and hepatocellular carcinoma. Hence, the primary approach to interrupt this cycle and diminish complications and overall patient outcomes is the identification of the condition early, proper glycemic control, lifestyle change, and a multidisciplinary approach.

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Diabetes And Cancer: The Metabolic-Oncologic Nexus

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1. Introduction: The Converging Epidemics of Diabetes and Cancer

Two of the biggest global health issues of the twenty-first century are cancer and type 2 diabetes mellitus (T2DM). Although these conditions have historically been studied separately, mounting epidemiological and mechanistic data have shown a strong reciprocal relationship between them, leading to the growing recognition of a Cardio-Renal-Metabolic-Cancer Syndrome. (Schnell & Standl, 2025) Examining epidemiological trends, molecular mechanisms, particular cancer types, therapeutic approaches, and clinical prevention techniques, this chapter delves into the intricate relationship between diabetes and cancer.

Over 537 million adults worldwide are thought to have type 2 diabetes, which has reached epidemic proportions. Meanwhile, the incidence of cancer is still rising, with almost 20 million new cases reported each year. In addition to obesity-related cancers like colorectal, kidney, endometrial, and breast cancers, people with diabetes have a 25–250% higher risk of developing a variety of cancers, including pancreatic and hepatocellular cancers. (Schnell & Standl, 2025) This increased risk is caused by basic pathophysiological mechanisms that connect metabolic dysfunction to tumorigenesis rather than just common risk factors like obesity and sedentary lifestyle.

The identification of this link between diabetes and cancer has significant ramifications for clinical practice, screening methods, and the creation of new therapeutic and preventive strategies. Comprehending the molecular foundations of this correlation presents unparalleled prospects for focused interventions that could concurrently improve metabolic and oncologic outcomes.

2. Epidemiological Evidence: The Magnitude and Specificity of Cancer Risk

2.1 Global Epidemiology and Incidence Patterns

People with type 2 diabetes consistently have higher cancer incidence and mortality, according to epidemiological studies conducted on several continents. Mesquita and associates, 2023 With hazard ratios for all-cancer mortality reaching 1.26 (95% CI 1.21–1.31) across 19 prospective population-based cohorts with over 771,297 participants, a thorough analysis from Asian populations showed that diabetes significantly increased the risk of total cancer death and total cancer incidence. (Noto, 2017) In particular, the incidence and mortality rates of colorectal cancer have been found to be 27% higher in diabetic patients than in non-diabetic controls, though this correlation varies by geographic location and socioeconomic status.

According to some studies, 50% of patients with pancreatic cancer develop diabetes either before or concurrently with their cancer diagnosis, demonstrating the reciprocal nature of the diabetes-cancer relationship. New-onset diabetes often represents an early manifestation of underlying malignancy. (Popovic and others, 2023) Instead of just diabetes causing cancer, this temporal relationship points to shared pathogenic mechanisms.

There is notable cancer-type specificity in the association between diabetes and cancer. Pancreatic cancer has the highest relative risk among solid tumours (HR 1.87, 95% CI 1.79-1.96), followed by colorectal cancer (1.30), hepatocellular carcinoma (1.70), endometrial cancer (1.63), and kidney cancer (1.41). (González et al., 2017) The risk of breast cancer is slightly higher (1.20 for postmenopausal women), but prostate cancer incidence is actually lower in diabetic men (HR 0.85), despite the fact that survival outcomes are significantly worse in diabetic men with prostate cancer. (Lutz and others, 2022)

This site-specific variation is a reflection of the differential involvement of insulin/IGF-1 signalling, chronic inflammation, and metabolic dysfunction in different tissues. Endocrine cancers, as well as those with a high metabolic mandate (pancreas, liver), associate most strongly with diabetes, and tissues most immediately responsive to sex hormones (breast, endometrium), are associated with intermediate risk increases.

2.3 Racial, Ethnic, and Socioeconomic Disparities

The emerging data show considerable heterogeneity on diabetes-cancer associations across racial and ethnic groups. (Miller et al., 2023) A retrospective cohort study of diabetic patients with breast cancer demonstrated that Glycaemic control positively correlated with triple-negative breast cancer incidence overall but only among non-Hispanic Whites, with 9.2 per cent TNBC against well-controlled diabetic and 21.9 per cent TNBC among glycaemic control diabetics, respectively. However, among Black patients, the proportion of TNBC (17.6% to 22.7%) remained unchanged across the glycaemic control categories, which implies either varying biologies or unmeasured confounding by the access of diabetes care and cancer screening.

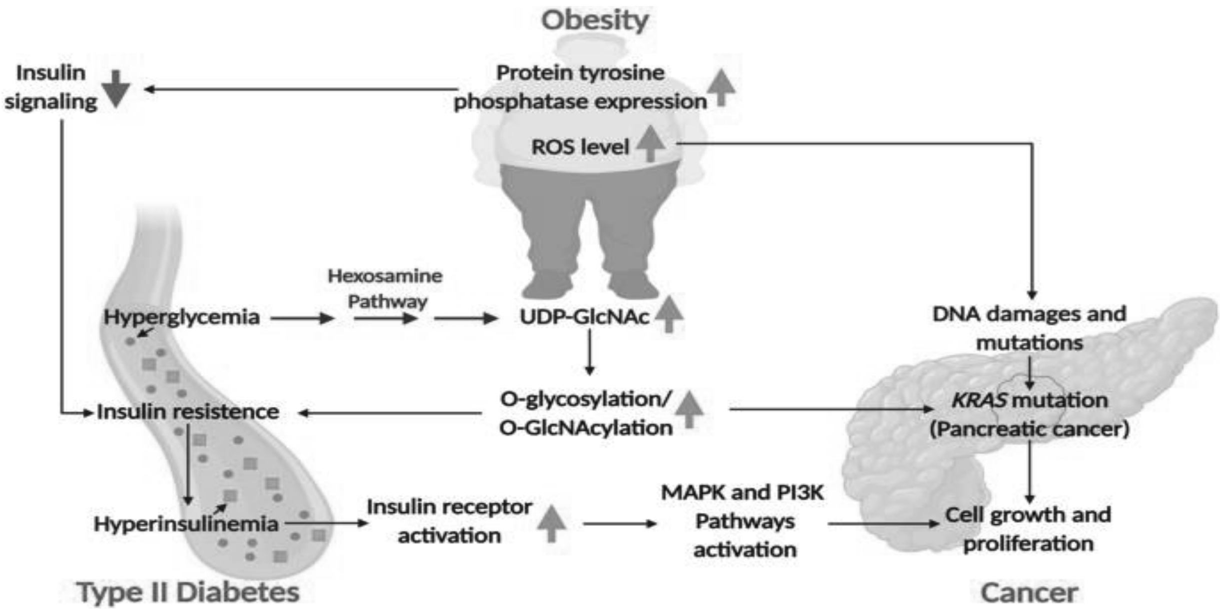

FIG. 1: *Association of type 2 diabetes, cancer, and obesity.*

The high levels of blood glucose in T2D cause upregulation of the hexosamine biosynthetic pathway. The upregulation of the hexosamine biosynthetic pathway causes high levels of UDP-GlcNAc, leading to O-glycosylation/O-GlcNAcylation. The high levels of O-glycosylation/O-GlcNAcylation can cause insulin resistance in T2D. The high levels of O-glycosylation/O-GlcNAcylation can also cause KRAS mutation in pancreatic cancer. The insulin resistance can cause hyperinsulinemia. The hyperinsulinemia can cause the activation of insulin receptors. The activation of insulin receptors can activate the MAPK and PI3K pathways, which can cause cancer cell growth. Obesity can cause the expression of protein tyrosine phosphatase. The expression of protein tyrosine phosphatase can cause insulin resistance. Obesity can cause the generation of ROS. The generation of ROS can cause DNA damages, leading to cancer. Blue circles represent glucose. Green squares represent insulin. (Zhang et al. 2021)

3. Molecular Mechanisms: From Metabolic Dysfunction to Tumorigenesis

3.1 Hyperinsulinemia and Insulin Resistance

The two main pathophysiological bridges connecting diabetes and cancer are hyperinsulinemia and insulin resistance. (Asiri et al., 2024) Type 2 diabetes is associated with a step-wise deterioration in beta-cell function and tissue insulin resistance, leading to hyperinsulinemia as a compensatory response. The hyperinsulinemia has several effects in the body that contribute to cancer formation. The high insulin level activates the phosphatidylinositol 3-kinase/protein kinase B/mammalian target of rapamycin (PI3K/Akt/mTOR) pathway, which is a key pathway in regulating cell growth, survival, proliferation, and anti-apoptotic activities in cancer cells. (Asiri et al., 2024)

Apart from the direct receptor activation, hyperinsulinemia also enhances the bioavailability of insulin-like growth factor-1 (IGF-1) by inhibiting the hepatic synthesis of IGF-binding proteins. (Chen et al., 2019) Thus, there is a clear trend of enhanced IGF-1 bioavailability in the context of insulin resistance, leading to a pro-oncogenic state of enhanced mitogenic activity and decreased apoptotic potential.

Epidemiological evidence also supports hyperinsulinemia as a mechanism, as evidenced by pathway-specific polygenic scores for increased insulin resistance with hyperinsulinemia that were associated with increased risk of colorectal cancer, with odds ratios ranging from 1.08 to 1.25 for metabolic syndrome and obesity-related scores. (Zhou et al.,2025)

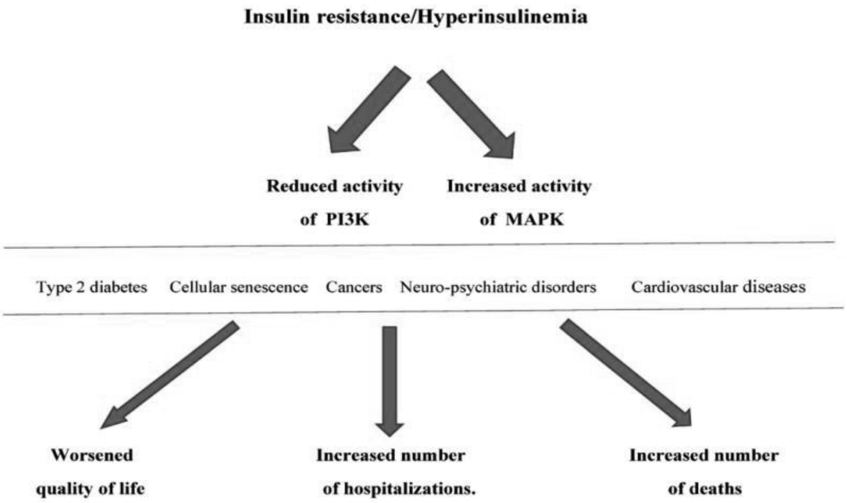

Fig. 2: *Actions of hyperinsulinemia on cardiovascular system. PI3K- Phosphatidylinositol-3 kinases; MAPK- mitogen-activated protein kinase; LV- left ventricle; VSMC- vascular smooth muscle cells; ED- endothelial dysfunction (Fazio et al., 2024)*

3.2 Hyperglycemia and Glucose Metabolism

The chronic hyperglycemia, which is a hallmark of uncontrolled diabetes, plays a role in cancer development through a variety of mechanisms. (Ayat et al., 2024). The hyperglycemia in cancer patients acts as an energy source for the rapid growth of cancer cells, which can be demonstrated by the Warburg effect, in which cancer cells have an increased rate of glucose consumption. The hyperglycemia in cancer patients leads to oxidative stress through the formation of advanced glycation end-products and the hexosamine biosynthetic pathway, which in turn leads to chronic inflammation and DNA damage.

The association between dysglycemia and cancer risk was found to be dose responsive in a United States-based study of 722,532 individuals from the National Health Interview Survey (1997-2013), with unadjusted odds ratios of 1.92 (95% CI, 1.78 to 2.08) for prediabetes and 2.20 (95% CI, 2.13 to 2.27) for diabetes. Importantly, this association remained significant even after adjusting for body mass index, with an adjusted odds ratio of 1.12 for prediabetes and 1.15 for diabetes. This indicates that hyperglycemia, in itself, plays an independent role in cancer risk

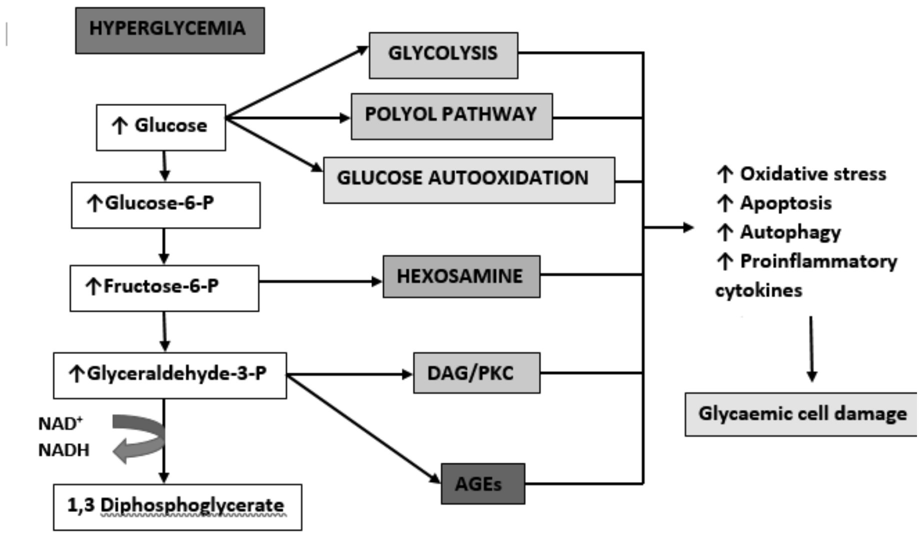

FIG.3: Principal molecular mechanisms involved in glycemic cell damage. Increased glucose concentrations may lead to increased glycolytic and polyol pathways, increased glucoxidation, elevated AGE formation, and activation of PKC and hexosamine pathways. AGE, advanced glycation-end products; DAG, diacylglycerol; PKC , protein kinase C; ROS , reactive oxygen species.

3.3 Oxidative Stress and Chronic Inflammation

The synergistic effect of hyperglycemia and hyperinsulinemia on the generation of reactive oxygen species (ROS) and oxidative stress is achieved through the following mechanisms. In particular, hyperglycemia promotes hyperglycemia-induced changes in the activity of mitochondrial respiration through increased glucose uptake, increased nicotinamide adenine dinucleotide phosphate oxidase (NADPH) and protein kinase C. (Chen et al., 2024)

This oxidative stress continues with chronic low grade inflammation, which is a characteristic of diabetes and cancer. Chronic hyperglycemia activates nuclear factor- 002B (NF- 002B) signaling promoting the synthesis of pro-inflammatory cytokines such as tumor necrosis factor-alpha (TNF- 002B), interleukin-6 (IL-6), and chemokines. These inflammatory mediators have direct effects of encouraging tumor cell growth and survival and also reduce anti-tumor immunity. Also, higher levels of adipokines like leptin during obesity induced diabetes further increase this state of inflammation. The authors of this study employ a qualitative research design to analyze the findings of the experiment. <|human|>The research design that the authors of this study use is the qualitative one to interpret the results of the experiment.

Derivatives of reactive oxygen metabolites (d-ROMs) and reduced total thiol levels (TTLs) are examples of oxidative stress markers that showed strong correlations with all-cause mortality in 2125 patients with type 2 diabetes, with pooled hazard ratios of 2.10 (95% CI 1.43-3.09) and 0. These links support the clinical importance of oxidative imbalance in diabetic patients at the risk of cancer. (Xuan et al., 2019)

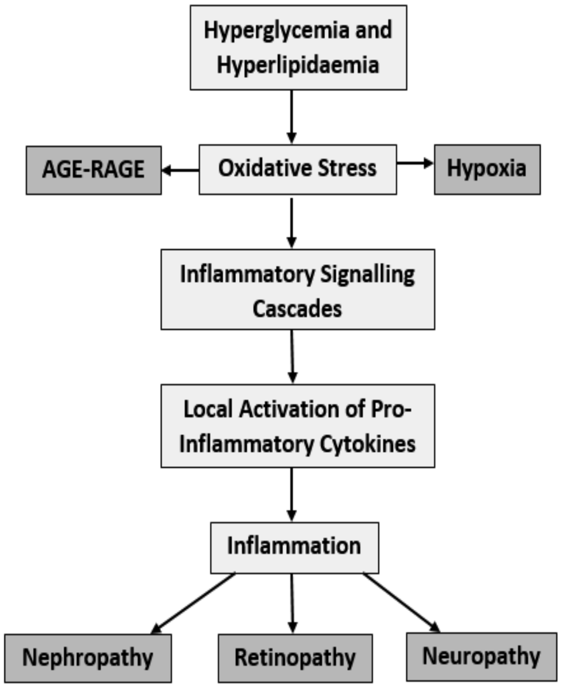

FIG.4: General pathway in the progression of diabetic microvascular complications (Nguyen et al. 2012)

3.4 IGF-1/Insulin Receptor Signalling in Cancer

One of the primary pathways through which diabetes and cancer are linked on the molecular level is insulin-like growth factor axis. IGF-1R is nearly expressed in cancer cells and elicits canonical pro-oncogenic signalling by mediating MAPK and PI3K/Akt signalling and inducing proliferation, inhibiting apoptosis, promoting angiogenesis and facilitating epithelial-mesenchymal transition. Generally, the article is very informative because the study findings are introduced in a systematic format.

The author gives a few reasons that made the event more marginalized, one of which is the fact that insulin promotes the production of IGF-1 by the ad due to its structural homology with the IGF-1 receptor.

MicroRNAs (miRNAs) and long non-coding RNAs (lncRNAs) are another type of non-coding RNAs that have been revealed to play a major role in the regulation of IGF-1R level and signalling by diabetes-related malignancy. Many miRNAs including miR-7, miR-139, miR-145, and miR-1 suppress the IGF-1R expression, and their down-regulation in diabetes gives out a free environment of higher IGF-1R-induced tumorigenesis.

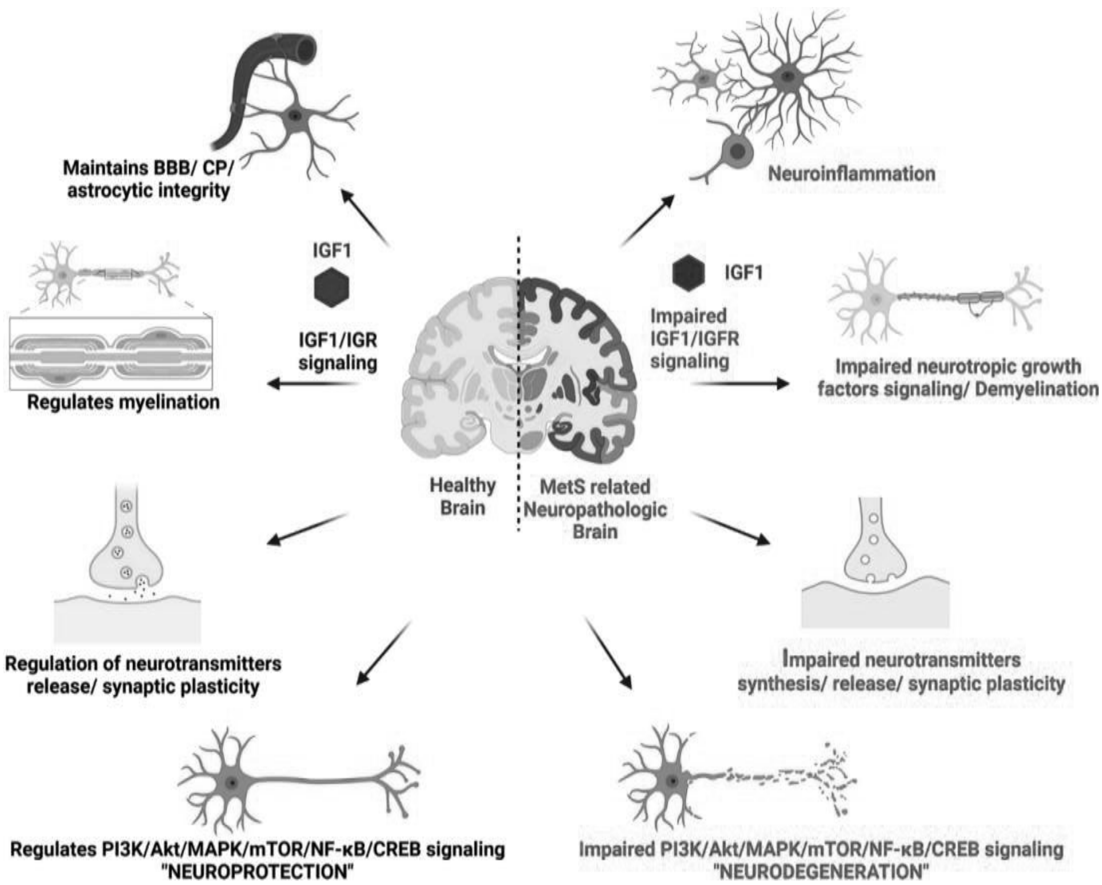

FIG.5: Diagrammatic picture on physiological and pathological action of IGF-1.

The cerebrovascular microenvironment and BBB/CP integrity, inflammation in microglia, and synaptic communication and cognition are regulated by IGF-1 in the normal brain, which is able to act on ionic channels and neurotransmitters. Systemic and local IGF-1 deficiency in Metabolic syndrome (MetS) related brain reveals the disrupted cerebrovascular microenvironment/disturbed BBB/CP integrity, enhanced the deposition of α-Synuclein/Tau/Aβ/HTT proteins lead to impaired neuroinflammatory action, neurotransmitter release, synaptic plasticity, and cognition which can result in neurodegener. (Arjunan et al., 2023)

3.5 Metabolic Reprogramming and Tumour Microenvironment

There is remarkable metabolic reprogramming of tumour microenvironment of diabetes-related cancer that is biased towards tumorigenesis. Hyperinsulinemia and hyperglycemia induces metabolic alterations in the immune cells, including enhanced glycolysis of the inflammatory macrophages, promoting the M1 polarization and increased secretion of TNF-alpha and IL-6.

Simultaneously, the Treg regulatory cell activity suffers damage, and this permits the cancer cells to evade the immune system.

Metabolic reprogramming also occurs in cancer cells themselves where hexosamine biosynthetic pathway flux and O-GlcNAcylation of oncoproteins promoting cancer cell survival and resistance to therapy are increased. In high glucose condition, unfolded protein response (UPR) occurs that cause endoplasmic reticulum stress that in fact enhances survival of cancer cell under selective pressures by more aggressive clones.

4. Diabetes and Major Cancer Types: Mechanisms and Epidemiology

4.1 Pancreatic Cancer

Pancreatic cancer is the association with type 2 diabetes with the highest level of association; relative risks are usually between 1.5-2.0. It is a two-way process: diabetes predisposes pancreatic cancer, and secondary diabetes which is caused by pancreatic cancer often has many mechanisms. Diabetes caused by tumor destruction of beta-cells, insulin resistance caused by tumor-secreted cytokines such as TNF-alpha and IL-6, and the distortion of the enterohepatic bile acid signaling to glucose homeostasis all contribute to the hyperglycemia caused by PaC. Correct upbringing of children should avoid encouraging the cultivation of violent behaviour. Raising children properly must not promote the development of violent behaviour.

The pathways involving T2DM to pancreatic carcinogenesis are chronic inflammation of the pancreas that causes dysplasia of the ductal epithelial cell, rise of intrapancreatic insulin levels that stimulate the growth of the ductal cell, hyperactivation of the IGF-1 pathway via elevation of bioavailability, and lipotoxic metabolite accumulation to induce The development of diabetes beyond age 50, with a rapid loss of weight or epigastric pain, should be investigated with a possible underlying pancreatic malignancy (George et al., 2022).

4.2 Colorectal Cancer

Colorectal cancer is roughly 30 percent more common among patients having type 2 diabetes as compared to non-diabetic controls. The mechanistic relationships are: Wnt/ β -catenin signalling hyperinsulinemia-stimulated, gut microbiota dysbiosis (altered abundance of beneficial and pathobiont bacteria), and increased circulating free bile acid-induced farnesoid X receptor signalling. Also, incessant hyperglycemia promotes epithelial cell injury and activates inflammatory reactions like NF- 81B that renders the environment conducive to the growth of adenoma and malignant transformation.

Metformin has emerged as a potential chemo preventive agent in patients with diabetic colorectal cancer and a statistically significant decrease of the risk of colorectal cancer (HR 0.71) and rectal cancer (0.49). Protective association was identified to be greater in the case of obese participants (BMI 30kg/m 2, HR 0.59) compared to non-obese participants (0.99). Epidemiologic implications of such results on metabolic-targeted cancer prevention methods are possible.

4.3 Hepatocellular Carcinoma

The third cause of cancer-related mortality in the entire globe and type 2 diabetes and metabolic syndrome may be viewed as independent risk factors of developing HCC, without cirrhosis. Pathophysiological connections have also been proposed as the non-alcoholic fatty liver disease (NAFLD) and the occurrence of non-alcoholic steatohepatitis (NASH) because of insulin resistance and oxidative stress accumulation, the presence of lipopolysaccharide translocation caused by gut dysbiosis, and hepatolithnus.

IGF-1R overexpression, high levels of IGF-2 and low levels of IGF-1 levels are found to have significant results with HCC and are linked to poor prognosis. Low concentrations of IGF-1 in diabetic conditions paradoxically elevate the risk of HCC through escalating hepatocyte proliferation by elevating growth-inhibitory pathways of IGF-1, but also hyperinsulinemia maintains the PI3K/Akt/mTOR signaling pro-mitogenic state of the hepatocyte due to the residual activation of IGF-1R and ins

4.4 Breast and Endometrial Cancers

The association of diabetes and hormone sensitive cancers is not identical as those of the metabolic cancers of breast cancer (postmenopausal) with moderate risk of increased (HR 1.20) and endometrial cancer moderate risk (HR 1.63). These pathways involve hyperinsulinemia which causes hyperplasia of the ovarian androgen-producing cells, reduced production of sex hormone-binding globulin in the liver and, therefore, increased circulating bioavailable estrogens. Otherwise, the obese diabetic women adipose tissue is where the expression of aromatase and the focal site of estrogen production takes place.

Women with type 2 diabetes who had poor glycaemic control were reported to have a higher incidence of triple-negative breast cancer (21.8% having HbA1c 9.5 or more vs 12.7% having

HbA1c less than 7.0) particularly women of non-Hispanic White origin. This association of molecular subtypes is to suggest that hyperglycemia can selectively augment hormone-independent and more aggressive forms of breast cancer by selectively programming the metabolism.

5. Therapeutic Interventions: Antidiabetic Agents and Cancer Risk Modification

5.1 Metformin: The Paradigm of Dual Benefits

One of the most popular antidiabetic drugs in the globe, Metformin, is a possible prototype of the therapeutic agents, which possess metabolic effects as well as anti-cancer effects. (Lawler et al., 2024) Metformin is able to stimulate AMP-activated protein kinase (AMPK) that inhibits mTOR signaling and cell proliferation and stimulates insulin sensitivity and decreases hepatic gluconeogenesis. The presence of the two effects in the management of diabetes and the cancer promoting pathways offer the opportunity to prevent cancer in the populations that have diabetes.

Some observational studies and meta-analyses have shown that metformin reduces the risk of developing cancer. A meta-analysis of the impact of metformin in colorectal cancer found that the use of metformin was linked to a very much lower risk (Ma et al., 2025). Moreover, the metformin management of patients with locally advanced rectal cancer using neoadjuvant chemo radiotherapy was associated with a better pathologic response compared to the treatment using control therapy with or without diabetes. Such results indicate that metformin can prevent and treat proven cancer either in the adjunct.

We must add that the anticancer mechanisms of action of metformin are: (1) direct, based on AMPK, the inhibition of mTOR-activation and cell growth; (2) indirect, via insulin sensitivity, the inhibition of the insulin level and bioavailability of IGF-1; (3) the modulation of the microbiota of the gut, which is oriented towards anti-inflammatory

5.2 SGLT2 Inhibitors and Novel Antidiabetic Agents

New antidiabetic agents with potential anti-cancer properties are SGLT2 inhibitors. (Benedetti et al., 2021) A meta-analysis of SGLT2 inhibitors demonstrated statistically significant protective effect (RR 0.35, 95% CI 0.33-0.37) and dapagliflozin (RR 0.06) and ertuglifozin (RR 0.22) in particular. The mechanisms which may be involved are the enhancement of metabolism of ketone bodies, the reduction of hyperglycemia, and potential immunomodulatory action though definitive studies concerning the mechanism have not been carried out yet.

GLP-1 receptor agonists as well have been mentioned in the context of anti-cancer agents and early findings show that colorectal cancer has been reducing in some populations. These agents help to increase the glycaemic level secreting glucose-dependent insulin and reduces the appetite and raises weight loss, both of which lower cancer risk (Vekic et al., 2021).

5.3 Insulin Use and Cancer Risk

The issue of insulin treatment and the risks of cancer has been a controversial one. Although there are reports, dating back to the early 1990s, indicating a higher risk of cancer with exogenous insulin administration, the current data show that insulin use to manage hyperglycemia is not likely to increase the likelihood of cancer occurrence when used in reasonable dosages (Yang and Chan, 2012). Rather, the most significant pathophysiological agent seems to be dysregulation of metabolic pathways as a result of insulin resistance and not insulin administration itself. Nevertheless, long term overuse of insulin treatment can also be a reason to monitor the risk of cancer in some groups of people.

6. Prevention, Screening, and Clinical Implications

6.1 Screening Strategies for Diabetes Patients

Advanced screening procedures are needed in order to detect cancer at an early stage amongst diabetic people. Pancreatic cancer should be considered as a possible diagnosis in the new-onset diabetes, especially among patients older than 50 years, with the help of imaging and measuring biomarkers such as CA 19-9. All the typical cancer types should be screened in diabetic patients according to their age, though the screening of colorectal, breast, and cervical cancer should be prioritized due to the scale of the risk increase.

Proteomic and metabolomics analysis of diabetic individuals could provide new biomarkers that could predict the risk of cancer allowing the categorization of risk and the use of personal surveillance techniques. As an example, the high level of circulating IGF-1 even with excellent glycaemic control is an indication of increased cancer surveillance. Individuals aged 20 to 24 years are identified as the vulnerable age group. The vulnerable age group is reported to be people between 20 to 24 years of age.

6.2 Lifestyle Interventions and Weight Reduction

Deliberate 10 per cent or higher reduction in weight of obese diabetic/ prediabetes patients in the intensive lifestyle intervention or bariatric surgery is related to the much lower incidence of obesity-related cancers. (Mesquita et al., 2023) Multifaceted lifestyle changes such as less energy consumption, exercise, and dietary habits optimization with the emphasis on whole grains, legumes, vegetables, and a restricted use of processed meat and sugar-sweetened drinks can be considered the key prevention strategies that can be applied to all diabetic patients.

6.3 Glycaemic Control and Cancer Outcomes

Although the relationship between hyperglycemia and cancer is apparent as it is evident that these two domains share mechanistic relationships, there is limited evidence that intensive glycaemic control is less likely to cause cancer. Nevertheless, it has been observed that patients who are better glycaemic-controlled exhibit slightly less cancer incidence and better cancer survival, which proves that glycaemic control is an effective element of cancer prevention strategy (Noto, 2017).

6.4 The Cardio-Renal-Metabolic-Cancer Syndrome Framework

An overhaul of paradigm shift towards a unitary approach of Cardio-Renal-Metabolic-Cancer Syndrome requires synergistic screening, management and prevention interventions. Diabetic cancer patients have suspected cancer, and renal assessment and cardiovascular risk stratification are required simultaneously since the two conditions have shared etiology and make treatment of cancer difficult to tolerate. (Standl & Schnell, 2025) On the other hand, cancer patients found to have diabetes should receive aggressive metabolic intervention in order to maximize cancer outcomes and minimise non-cancer mortality.

Conclusion

The latter presents a type 2 diabetes and cancer bi-directional correlation as one of the most observable health issues of the developed world and the latter provide phenomenal intervention opportunities on the other. The knowledge of the molecular pathways that would connect these diseases, i.e., the centrally acting hyperinsulinemia, hyperglycemia, oxidative stress, chronic inflammation and aberrant growth factor signalling, can be included in the development of focus prevention and treatment strategies, which would prove useful both in metabolic and oncologic outcome.

The other is the new antidiabetic drugs of pleiotropic biological properties which is likely to prevent cancer to diabetic patients as opposed to metformin. In fact, a mechanistic evidencing but that optimum cancer prevention should be applied with paramount metabolic caution such as glycaemic repression, weight loss, lifestyle changes and the greatest care when using antidiabetic agents in the presence of their properties with regard to cancer.

When implementing the further researches, he/she will have to consider:

(1) The illustration of the causal processes with the help of the molecular epidemiology and functional research;

(2) Discovery of metabolomics and proteomic biomarkers that could be used to pre-empt the existence of the risk of cancer in diabetic patients;

(3) screening policy combination development and research;

(4) conducting high quality randomised controlled trials that border the use of certain antidiabetic agents to prevent cancer;

(5) the introduction of integrated care models, which deal with metabolic and oncologic outcomes.

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Nutrition and Lifestyle Management

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Medical Nutrition Therapy in Diabetes

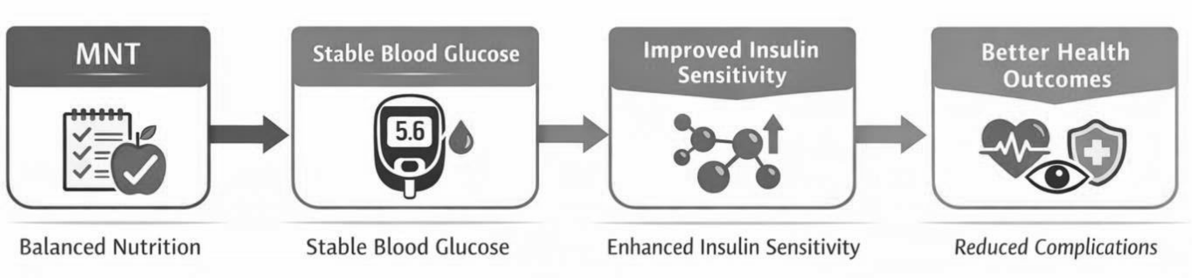
1. Introduction: Medical Nutrition Therapy (MNT) refers to an evidence-based, individualized nutritional intervention designed to prevent, manage, and treat chronic metabolic disorders, including diabetes mellitus. It encompasses comprehensive nutritional assessment, diagnosis, intervention, and continuous monitoring to achieve specific metabolic and clinical outcomes. Within the context of diabetes care, MNT is recognized as a foundational therapeutic strategy and is consistently recommended as a first-line intervention for optimizing glycaemic control and mitigating long-term complications (Evert et al., 2019; American Diabetes Association, 2024).

Diabetes mellitus is a complex, multifactorial metabolic disorder characterized by chronic hyperglycaemia arising from defects in insulin secretion, insulin action, or both. Persistent hyperglycaemia contributes to widespread metabolic dysregulation, leading to both microvascular and macrovascular complications. Given the central role of dietary intake in glucose homeostasis, targeted nutritional interventions are critical for modulating metabolic pathways and improving clinical outcomes.

2. Therapeutic Goals of MNT in Diabetes

The overarching objective of MNT is to achieve and sustain optimal glycaemic control while ensuring nutritional adequacy and metabolic stability. Glycaemic regulation is typically evaluated through glycated haemoglobin (HbA1c), with a general target of <7% for most adults; however, individualized targets ranging from 6.5% to 8% are often adopted based on patient-specific factors, including age, disease duration, comorbidities, and hypoglycaemia risk (American Diabetes Association, 2024).

Beyond glycaemic control, MNT aims to attenuate cardiometabolic risk by improving lipid profiles, reducing systemic inflammation, and optimizing blood pressure levels. It also seeks to prevent or delay the onset of diabetes-related complications such as nephropathy, neuropathy, and retinopathy. Importantly, MNT contributes to the maintenance of healthy body weight and the reduction of visceral adiposity, both of which are closely linked to insulin resistance (Bhupathiraju & Hu, 2016).



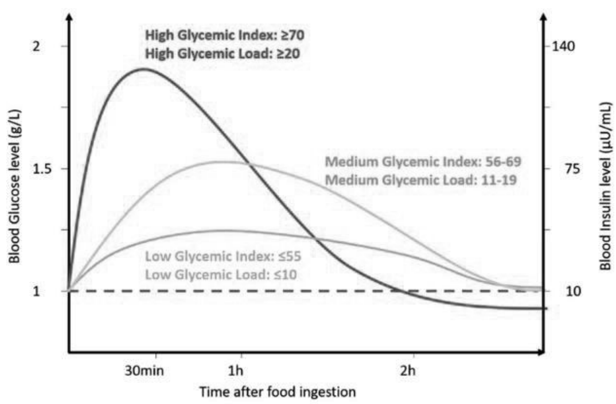
3. Macronutrient Composition and Metabolic Regulation

Macronutrient distribution plays a pivotal role in determining glycaemic responses and overall metabolic homeostasis in individuals with diabetes. The interplay between carbohydrates, proteins, and fats significantly influences insulin dynamics, postprandial glucose excursions, and long-term metabolic outcomes.

3.1 Carbohydrates and Glycaemic Dynamics

Carbohydrates are the principal drivers of postprandial glycaemia, necessitating precise regulation of both their quantity and quality. Current dietary recommendations suggest that carbohydrates contribute approximately 45–60% of total daily energy intake; however, this distribution must be individualized to align with glycaemic targets and metabolic responses (ADA, 2024).

The glycaemic index (GI) serves as a critical tool in evaluating carbohydrate quality by quantifying the rate at which foods elevate blood glucose levels. Diets emphasizing low-GI foods have been shown to attenuate postprandial



hyperglycaemia, reduce glycaemic variability, and improve insulin sensitivity (Jenkins et al., 2012; Reynolds et al., 2019). Glycaemic load (GL), which incorporates both carbohydrate quality and quantity, provides a more comprehensive assessment of dietary glycaemic impact.

Carbohydrate counting further enhances glycaemic control, particularly in individuals receiving insulin therapy, by enabling precise matching of insulin dosage with carbohydrate intake. The prioritization of complex carbohydrates—such as whole grains, legumes, and vegetables—facilitates sustained glucose release and improved metabolic stability.

3.2 Protein Intake and Metabolic Modulation

Proteins typically account for 15–20% of total energy intake and contribute to metabolic regulation through their effects on satiety, muscle preservation, and glucose metabolism. While proteins exert minimal direct impact on postprandial glycaemia, they influence insulin secretion and may indirectly modulate glucose homeostasis.

Excessive protein intake, however, warrants caution in individuals with diabetic nephropathy, as it may exacerbate renal dysfunction. The inclusion of plant-based protein sources, such as legumes and pulses, is particularly advantageous due to their combined provision of dietary fiber, micronutrients, and bioactive compounds that support metabolic health (Ley et al., 2014).

3.3 Dietary Fats and Cardiometabolic Risk

Dietary fats constitute approximately 20–35% of total energy intake and play a crucial role in cardiovascular risk modulation. The quality of fat intake is of paramount importance in individuals with diabetes, given their heightened susceptibility to cardiovascular disease.

Monounsaturated and polyunsaturated fatty acids, derived from sources such as nuts, seeds, and vegetable oils, have been shown to improve lipid profiles and reduce inflammation. Conversely, saturated fats should be restricted to less than 10% of total energy intake, while trans fats should be eliminated due to their deleterious effects on lipid metabolism and cardiovascular health (American Diabetes Association, 2024).

4. Dietary Fiber and Glycaemic Modulation

Dietary fiber represents a critical component of MNT due to its multifaceted role in glycaemic regulation and metabolic health. A daily intake of 25–30 grams is generally recommended for individuals with diabetes (American Diabetes Association, 2024).

Soluble fiber exerts a significant modulatory effect on glycaemic control by delaying gastric emptying, attenuating intestinal glucose absorption, and enhancing insulin sensitivity. Additionally, fiber fermentation in the colon produces short-chain fatty acids, which further contribute to metabolic regulation and anti-inflammatory effects (Reynolds et al., 2019).

High-fiber dietary patterns are consistently associated with improved glycaemic outcomes, reduced lipid levels, and enhanced satiety, thereby supporting long-term weight management.

Macronutrient	Recommended Intake	Key Considerations
Carbohydrates	**45–60%** of total calories	• Focus on low-GI, high-fiber foods; • Monitor carbohydrate counting
Protein	**15–20%** of total calories	• Moderate intake; • Emphasize plant-based sources
Fats	**20–35%** of total calories	• Prioritize unsaturated fats; • Limit saturated and trans fats

5. Meal Planning and Dietary Structuring

Structured meal planning is integral to the effective implementation of MNT. The distribution of food intake across regular intervals facilitates stable glycaemic control and minimizes fluctuations in blood glucose levels.

The plate method provides a practical framework for achieving balanced nutrient intake, emphasizing appropriate proportions of non-starchy vegetables, complex carbohydrates, and protein sources. Consistency in meal timing is particularly important for individuals on insulin or insulin secretagogues, as it reduces the risk of hypoglycaemia.

Furthermore, limiting the intake of refined sugars, sugar-sweetened beverages, and ultra-processed foods is essential for maintaining glycaemic stability. Adequate hydration and mindful eating practices further enhance dietary adherence and metabolic outcomes.

6. Weight Management and Energy Homeostasis

Weight management constitutes a cornerstone of diabetes care, particularly in the context of type 2 diabetes, where obesity is a primary driver of insulin resistance. Central adiposity is strongly associated with impaired insulin signalling and adverse metabolic outcomes (Bhupathiraju & Hu, 2016).

A modest weight reduction of 5–10% has been demonstrated to significantly improve glycaemic control, insulin sensitivity, and lipid metabolism (Lean et al., 2018). Achieving this requires the establishment of a negative energy balance through controlled caloric intake and increased physical activity.

Sustainable weight management strategies, including gradual dietary modifications and behavioural interventions, are essential for long-term success.

7. Clinical Evidence and Outcomes of MNT

Robust clinical evidence underscores the efficacy of MNT in diabetes management. Dietary interventions have been shown to reduce HbA1c levels by approximately 1–2%, a magnitude comparable to certain pharmacological therapies (Evert et al., 2019).

In addition to glycaemic improvements, MNT contributes to reductions in blood pressure, improvements in lipid profiles, and decreased systemic inflammation. Furthermore, in high-risk populations, appropriate nutritional interventions can delay or prevent the onset of type 2 diabetes (Ley et al., 2014).

The effectiveness of MNT is contingent upon patient adherence, continuous monitoring, and the provision of individualized nutritional counselling.

8. Integration within Comprehensive Diabetes Management

While MNT constitutes the foundation of diabetes care, its effectiveness is significantly enhanced when integrated with other lifestyle interventions. Physical activity improves insulin sensitivity and facilitates glucose uptake, thereby complementing dietary strategies.

Behavioural modifications, including goal setting, self-monitoring, and patient education, play a critical role in sustaining long-term adherence to dietary recommendations. Emerging research also highlights the interaction between diet and metabolic pathways, further reinforcing the importance of a comprehensive approach to diabetes management.

9. Conclusion

Medical Nutrition Therapy represents a scientifically grounded and clinically effective approach to diabetes management. By emphasizing individualized dietary planning, optimized macronutrient distribution, and evidence-based nutritional strategies, MNT plays a pivotal role in improving glycaemic control and reducing the burden of diabetes-related complications.

PART -2, Functional Foods and Nutraceuticals in Diabetes

1. Introduction

Functional foods and nutraceuticals have gained considerable attention as adjunct strategies in the management of diabetes mellitus due to their potential to modulate key metabolic pathways. Functional foods are defined as foods that provide health benefits beyond basic nutrition, whereas nutraceuticals refer to bioactive compounds derived from food sources that exert therapeutic effects (Roberfroid, 2000). In the context of diabetes, these dietary components play a significant role in addressing oxidative stress, chronic inflammation, and insulin resistance, which are central to disease progression (Sabu & Kuttan, 2002).

With the global rise in diabetes prevalence, there is an increasing emphasis on non-pharmacological interventions that can complement standard medical care. Functional foods and nutraceuticals offer a promising approach by targeting underlying metabolic disturbances and improving overall glycaemic control.

2. Classification of Functional Foods and Nutraceuticals

Functional foods can be broadly categorized into natural, fortified, enriched, and enhanced foods. Natural functional foods include whole grains, fruits, vegetables, legumes, and fermented products, which inherently contain bioactive compounds. Fortified and enriched foods, on the other hand, are modified to enhance their nutritional value by adding specific nutrients.

Nutraceuticals are typically classified based on their chemical composition and biological activity. Major categories include polyphenols, dietary fibers, probiotics, prebiotics, omega-3 fatty acids, and micronutrient supplements. These compounds influence metabolic processes through diverse mechanisms, including antioxidant activity, modulation of gut microbiota, and improvement of insulin signalling pathways (Pandey & Rizvi, 2009).

3. Role of Bioactive Compounds in Glycaemic Regulation

3.1 Polyphenols and Antioxidants

Polyphenols are plant-derived bioactive compounds widely present in fruits, vegetables, tea, and whole grains. They exert potent antioxidant effects by scavenging free radicals and reducing oxidative stress, which is a major contributor to beta-cell dysfunction and insulin resistance (Pandey & Rizvi, 2009).

In addition, polyphenols influence glucose metabolism by inhibiting carbohydrate-digesting enzymes such as α-amylase and α-glucosidase, thereby reducing postprandial glucose levels. They also enhance insulin sensitivity and improve endothelial function, contributing to better glycaemic control (Hanhineva et al., 2010).

3.2 Dietary Fiber as a Functional Component

Dietary fiber, particularly soluble fiber, plays a crucial role as a functional food component in diabetes management. It delays gastric emptying, reduces glucose absorption, and improves postprandial glycaemic response (Anderson et al., 2009).

High-fiber diets have been associated with improved insulin sensitivity and reduced risk of type 2 diabetes. Moreover, fiber fermentation in the colon produces short-chain fatty acids, which have beneficial effects on glucose metabolism and inflammation (Slavin, 2013).

3.3 Omega-3 Fatty Acids

Omega-3 fatty acids, found in fatty fish, flaxseeds, and walnuts, are known for their anti-inflammatory properties. While their direct impact on blood glucose levels is modest, they significantly improve lipid profiles and reduce cardiovascular risk, which is particularly important in individuals with diabetes (Calder, 2015).

3.4 Probiotics and Prebiotics

Probiotics and prebiotics represent an important category of functional components that influence metabolic health through the modulation of gut microbiota. Probiotics introduce beneficial microorganisms, while prebiotics promote their growth.

These components enhance insulin sensitivity, reduce systemic inflammation, and improve metabolic outcomes. Although the detailed role of gut microbiota is discussed separately, their functional relevance in diabetes management is increasingly recognized (Gibson et al., 2017).

4. Functional Foods in Diabetes Management

The incorporation of functional foods into daily dietary patterns provides a practical approach to improving glycaemic control. Whole grains, legumes, nuts, seeds, and fermented foods contribute to metabolic regulation through their combined effects on glucose absorption, insulin sensitivity, and inflammation.Dietary patterns rich in functional foods, such as plant-based and Mediterranean diets, have been consistently associated with improved glycaemic outcomes and reduced risk of complications. These diets emphasize minimally processed foods and a high intake of fiber, antioxidants, and healthy fats, which collectively support metabolic homeostasis (Esposito et al., 2014).

Functional Components and Their Role in Diabetes Management

Functional Component	**Food Sources**	**Mechanism of Action**	**Clinical Benefit**
Polyphenols	Fruits, tea, and vegetables	Antioxidant activity, enzyme inhibition	Improves insulin sensitivity
Dietary Fiber	Whole grains, legumes	Delays glucose absorption	Reduces postprandial glucose
Omega-3 Fatty Acids	Fish, flaxseeds	Anti-inflammatory action	Improves lipid profile
Probiotics	Yogurt, fermented foods	Modulates gut microbiota	Enhances metabolic health
Prebiotics	Garlic, onion, oats	Promotes beneficial bacteria	Improves insulin response

5. Nutraceuticals as Adjunct Therapeutic Agents

Nutraceuticals are increasingly used as complementary interventions in diabetes management. Micronutrients such as magnesium, chromium, and vitamin D have been investigated for their role in insulin action and glucose metabolism. Deficiencies in these nutrients are often associated with impaired glycaemic control (Barbagallo & Dominguez, 2015).

Herbal nutraceuticals, including cinnamon and fenugreek, have demonstrated hypoglycaemic effects by improving insulin sensitivity and reducing glucose absorption. However, variability in dosage, formulation, and bioavailability limits their widespread clinical application (Sabu & Kuttan, 2002).It is important to emphasize that nutraceuticals should not replace pharmacological therapy but may serve as supportive agents within a comprehensive management framework.

Mechanism of Functional Foods and Nutraceuticals in Diabetes Management

Functional Foods & Nutraceuticals

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Bioactive Compounds

(Polyphenols, Fiber, Omega-3)

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Reduced Oxidative Stress

↓ ↓

Improved Insulin Sensitivity Reduced Inflammation

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Better Glycaemic Control

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Reduced Risk of Complications

6. Clinical Evidence and Limitations

A substantial body of research supports the role of functional foods and nutraceuticals in improving metabolic parameters in individuals with diabetes. Studies have reported reductions in postprandial glucose levels, improvements in lipid profiles, and decreased markers of inflammation.

However, the evidence remains heterogeneous due to differences in study design, population characteristics, and intervention protocols. Long-term safety and efficacy data for many nutraceuticals are still limited, highlighting the need for further research.

7. Integration into Dietary Practice

The integration of functional foods into routine dietary practices represents a sustainable and culturally adaptable strategy for diabetes management. Emphasis should be placed on whole, minimally processed foods that naturally contain bioactive compounds.

Public health initiatives and nutritional education play a crucial role in promoting the adoption of such dietary patterns. A food-based approach is generally preferred over supplementation, as it provides a synergistic combination of nutrients and bioactive compounds.

8. Conclusion

Functional foods and nutraceuticals constitute an important dimension of dietary management in diabetes. Through their bioactive components, they modulate oxidative stress, inflammation, and insulin resistance, thereby improving metabolic outcomes.

While functional foods can be safely incorporated into daily diets, nutraceuticals should be used judiciously and under professional supervision. Their integration into comprehensive diabetes care highlights the importance of a holistic and evidence-based approach.

PART-3, Traditional Diets and Millets in Diabetes Management

1. Introduction

Traditional dietary systems have long been recognized for their role in promoting health and preventing chronic diseases. In recent years, there has been renewed scientific interest in traditional diets, particularly in the context of non-communicable diseases such as diabetes mellitus. These diets, characterized by the consumption of whole, minimally processed foods, offer a nutritionally balanced and culturally sustainable approach to disease management.

Millets, a group of small-seeded cereals traditionally consumed in many parts of Asia and Africa, have emerged as nutritionally superior grains with significant potential in diabetes management. Their low glycaemic index, high dietary fiber content, and rich micronutrient profile make them particularly suitable for individuals with impaired glucose metabolism (Saleh et al., 2013). Integrating millets into modern dietary practices provides an opportunity to bridge traditional knowledge with contemporary nutritional science.

2. Traditional Diets: Concept and Nutritional Significance

Traditional diets are defined as dietary patterns that are indigenous to a particular region and are based on locally available, seasonal, and minimally processed foods. These diets typically include whole grains, legumes, fruits, vegetables, and fermented foods, and are often low in refined sugars and unhealthy fats.

Such dietary patterns are inherently rich in dietary fiber, antioxidants, and phytochemicals, which contribute to improved metabolic health. Epidemiological studies have consistently demonstrated that populations adhering to traditional dietary patterns exhibit lower prevalence of metabolic disorders, including type 2 diabetes (Satija et al., 2016).

In contrast, the transition towards Westernized diets, characterized by high consumption of refined carbohydrates, processed foods, and saturated fats, has been associated with an increased risk of obesity and diabetes. Therefore, the revival of traditional dietary practices is increasingly being recognized as a viable strategy for chronic disease prevention.

3. Millets: Nutritional Composition and Health Benefits

Millets are nutritionally dense cereals that include varieties such as finger millet (ragi), pearl millet (bajra), and foxtail millet. They are rich in complex carbohydrates, dietary fiber, essential amino acids, vitamins, and minerals such as magnesium, iron, and calcium.

One of the key nutritional advantages of millets is their high fiber content, which contributes to slower digestion and gradual glucose release. Additionally, millets contain bioactive compounds such as polyphenols, which exhibit antioxidant and anti-inflammatory properties (Saleh et al., 2013).

The nutrient composition of millets makes them particularly beneficial for metabolic health, as they support improved glycaemic control, enhanced satiety, and better lipid metabolism.

4. Glycaemic Properties of Millets

The glycaemic index (GI) of foods is a critical determinant of their impact on blood glucose levels. Millets generally have a low to moderate GI, which makes them suitable for individuals with diabetes. Low-GI foods result in a gradual increase in blood glucose levels, thereby reducing postprandial glycaemic spikes.

The high fiber and resistant starch content of millets further contribute to their favorable glycaemic properties by slowing carbohydrate digestion and absorption. Studies have shown that replacing refined grains with millets can significantly reduce postprandial glucose levels and improve overall glycaemic control (Anitha et al., 2017).

Mechanism of Millets in Diabetes Management

Millets Consumption

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High Fiber + Low Glycaemic Index

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Slower Glucose Absorption

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Reduced Postprandial Glycaemia

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Improved Insulin Sensitivity

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Better Glycaemic Control

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Reduced Risk of Diabetes Complications

5. Role of Millets in Diabetes Management

The inclusion of millets in dietary patterns has been associated with multiple metabolic benefits in individuals with diabetes. Regular consumption of millet-based foods has been shown to improve insulin sensitivity, reduce fasting blood glucose levels, and lower HbA1c values.

Millets also contribute to weight management by enhancing satiety and reducing overall caloric intake. Their high fiber content promotes prolonged digestion, which helps in controlling appetite and preventing overeating.

In addition, millets have a positive effect on lipid metabolism, contributing to reduced levels of total cholesterol and low-density lipoprotein (LDL) cholesterol. These effects collectively reduce the risk of cardiovascular complications associated with diabetes (Anitha et al., 2017).

Nutritional Composition and Glycaemic Benefits of Selected Millets

Millet Type	Key Nutrients	Glycaemic Property	Health Benefits
Finger Millet (Ragi)	Calcium, fiber, amino acids	Low GI	Improves glycaemic control, bone health
Pearl Millet (Bajra)	Iron, magnesium, fiber	Moderate GI	Enhances insulin sensitivity
Foxtail Millet	Protein, fiber	Low GI	Reduces postprandial glucose
Little Millet	Fiber, antioxidants	Low GI	Improves metabolic stability
Barnyard Millet	Iron, resistant starch	Low GI	Supports weight management

6. Traditional Dietary Practices and Cultural Relevance

Traditional diets that incorporate millets are deeply rooted in cultural practices and local food systems. In many rural and tribal communities, millets have been a staple food for centuries due to their adaptability to diverse climatic conditions and low agricultural input requirements.

The cultural acceptability of millet-based foods enhances their potential for long-term dietary adherence. Unlike restrictive dietary interventions, traditional diets offer a sustainable and practical approach to diabetes management.

However, urbanization and changing food preferences have led to a decline in millet consumption, highlighting the need for renewed awareness and promotion of these traditional grains.

7. Challenges and Barriers to Adoption

Despite their nutritional benefits, several challenges limit the widespread adoption of millets in modern diets. These include limited consumer awareness, perceived inconvenience in preparation, and lack of availability in urban markets.

Additionally, taste preferences and the increasing popularity of refined grains pose significant barriers. Addressing these challenges requires targeted interventions, including public health campaigns, product innovation, and policy support to promote millet consumption.

8. Future Perspectives and Policy Implications

The promotion of millets aligns with broader public health and sustainability goals. Governments and international organizations are increasingly recognizing the importance of millets in addressing food security, nutrition, and climate resilience.

Policy initiatives aimed at integrating millets into public distribution systems, school feeding programs, and dietary guidelines can significantly enhance their consumption. Furthermore, research on value-added millet products and consumer-friendly formulations can improve their acceptability.

9. Conclusion

Traditional diets and millets represent a nutritionally rich and culturally sustainable approach to diabetes management. Their favorable glycaemic properties, high fiber content, and bioactive compounds contribute to improved metabolic outcomes and reduced risk of complications.The integration of millets into modern dietary practices offers a promising strategy for addressing the growing burden of diabetes. Promoting awareness, improving accessibility, and supporting policy initiatives are essential to harness their full potential.

PART-4, Physical Activity, Yoga and Lifestyle Interventions in Diabetes

1. Introduction

Diabetes mellitus is a multifactorial metabolic disorder in which lifestyle factors play a central role in both disease onset and progression. Among these, physical inactivity, sedentary behaviour, and chronic stress are significant contributors to insulin resistance and poor glycaemic control. Consequently, lifestyle interventions, including physical activity and mind–body practices such as yoga, have emerged as essential components of comprehensive diabetes management.

Unlike pharmacological therapies that primarily target specific metabolic pathways, lifestyle interventions exert systemic effects by modulating glucose metabolism, improving insulin sensitivity, and reducing cardiometabolic risk factors. These interventions are cost-effective, sustainable, and applicable across diverse populations, making them particularly relevant in the context of rising diabetes prevalence (Colberg et al., 2016).

2. Role of Physical Activity in Glycaemic Regulation

Physical activity plays a fundamental role in regulating glucose homeostasis through both insulin-dependent and insulin-independent mechanisms. During exercise, skeletal muscle contraction stimulates glucose uptake via translocation of glucose transporter type 4 (GLUT4) to the cell membrane, independent of insulin action. This results in an immediate reduction in blood glucose levels.

Regular physical activity also enhances insulin sensitivity by improving mitochondrial function, reducing intramuscular lipid accumulation, and increasing muscle mass. These adaptations contribute to improved glycaemic control over time and reduce insulin resistance, which is a hallmark of type 2 diabetes (Hawley & Lessard, 2008).

Additionally, physical activity influences hepatic glucose production and promotes better utilization of circulating glucose, thereby maintaining overall metabolic balance.

3. Types of Physical Activity and Their Effects

3.1 Aerobic Exercise

Aerobic exercise, such as walking, cycling, and swimming, is widely recommended for individuals with diabetes due to its positive effects on cardiovascular health and glucose metabolism. Moderate-intensity aerobic activity improves insulin sensitivity and reduces fasting and postprandial blood glucose levels.

Clinical guidelines recommend at least 150 minutes of moderate-intensity aerobic exercise per week, distributed over at least three days, with no more than two consecutive days without activity (American Diabetes Association, 2024).

3.2 Resistance Training

Resistance training, including weight lifting and strength exercises, plays a crucial role in improving muscle mass and metabolic function. Increased muscle mass enhances glucose uptake and storage, thereby improving glycaemic control.

Studies have shown that combining resistance training with aerobic exercise produces superior metabolic outcomes compared to either modality alone. Resistance training is typically recommended at least two to three times per week (Colberg et al., 2016).

3.3 Sedentary Behaviour and Its Impact

Prolonged sedentary behaviour, such as extended periods of sitting, has been identified as an independent risk factor for metabolic dysfunction. Even in individuals who meet exercise guidelines, excessive sedentary time can impair glucose metabolism and increase insulin resistance.

Interrupting sedentary behaviour with short bouts of light activity has been shown to improve postprandial glucose regulation, highlighting the importance of reducing overall sedentary time (Dempsey et al., 2016).

4. Yoga and Mind–Body Interventions

Yoga is a holistic practice that integrates physical postures (asanas), breathing techniques (pranayama), and meditation. It has gained increasing recognition as a complementary intervention in diabetes management.

Yoga exerts beneficial effects through multiple mechanisms, including reduction of stress-induced cortisol levels, improvement of autonomic nervous system balance, and enhancement of insulin sensitivity. Chronic stress is known to contribute to hyperglycaemia through hormonal pathways; therefore, stress-reducing practices such as yoga play a significant role in glycaemic regulation (Innes & Selfe, 2016).

Clinical studies have demonstrated that regular yoga practice can lead to reductions in fasting blood glucose, HbA1c levels, and lipid parameters. Additionally, yoga improves psychological well-being, which is essential for long-term disease management.

Types of Physical Activity and Their Effects on Glycaemic Control

Type of Activity	Examples	Mechanism of Action	Clinical Benefits
Aerobic Exercise	Walking, cycling, swimming	Increases glucose uptake via GLUT4	Reduces blood glucose levels

Type of Activity	Examples	Mechanism of Action	Clinical Benefits
Resistance Training	Weight lifting, strength training	Enhances muscle mass and insulin sensitivity	Improves glycaemic control
Flexibility Exercises	Stretching, mobility exercises	Improves joint function and mobility	Supports overall physical function
Yoga	Asanas, pranayama, meditation	Reduces stress hormones, improves autonomic balance	Enhances metabolic and psychological health
Light Activity Breaks	Standing, short walks	Interrupts sedentary behaviour	Improves postprandial glucose

5. Lifestyle Interventions and Behavioural Modification

Lifestyle modification extends beyond physical activity to include behavioural and psychosocial factors that influence health outcomes. Key components include dietary adherence, sleep quality, stress management, and self-monitoring of blood glucose.

Behavioural strategies such as goal setting, self-monitoring, and motivational support are essential for sustaining long-term lifestyle changes. Patient education and counselling play a critical role in improving adherence to lifestyle interventions.

Sleep is another important factor in metabolic regulation. Poor sleep quality and sleep deprivation have been associated with increased insulin resistance and impaired glucose tolerance. Therefore, maintaining adequate sleep duration and quality is an integral part of lifestyle management.

6. Weight Management and Metabolic Outcomes

Weight management is closely linked to lifestyle interventions and plays a crucial role in diabetes management. Physical activity contributes to energy expenditure and supports weight loss, while also improving body composition.

Even modest weight reduction (5–10% of body weight) has been shown to significantly improve insulin sensitivity, glycaemic control, and cardiovascular risk factors (Lean et al., 2018).

Lifestyle interventions that combine physical activity with dietary modification are particularly effective in achieving sustainable weight loss.

7. Clinical Evidence and Outcomes

A substantial body of evidence supports the effectiveness of lifestyle interventions in diabetes management. Structured exercise programs have been shown to reduce HbA1c levels by approximately 0.5–1%, along with improvements in lipid profiles and blood pressure (Colberg et al., 2016).

Yoga-based interventions have also demonstrated beneficial effects on glycaemic control and psychological well-being. Furthermore, lifestyle interventions have been shown to delay or prevent the onset of type 2 diabetes in high-risk individuals.

The effectiveness of these interventions depends on consistency, adherence, and individualized program design.

8. Integration into Comprehensive Diabetes Care

Physical activity, yoga, and lifestyle interventions should be integrated into routine diabetes care as part of a comprehensive management strategy. These interventions complement medical and nutritional therapies by addressing multiple aspects of metabolic health.

A multidisciplinary approach involving healthcare professionals, including physicians, dietitians, and exercise specialists, is essential for optimizing outcomes. Personalized intervention plans that consider individual preferences, capabilities, and cultural contexts enhance adherence and effectiveness.

9. Conclusion

Physical activity, yoga, and lifestyle interventions represent essential pillars of diabetes management. Through their multifaceted effects on glucose metabolism, insulin sensitivity, and overall metabolic health, these interventions provide sustainable and cost-effective strategies for improving clinical outcomes.

The integration of structured exercise, stress management, and behavioral modification into daily routines is critical for achieving long-term glycaemic control and reducing the burden of diabetes. As the prevalence of diabetes continues to rise, lifestyle-based approaches will play an increasingly important role in both prevention and management.

PART-5, Gut Microbiota and Glycaemic Control

1. Introduction

The human gut microbiota, comprising trillions of microorganisms including bacteria, viruses, and fungi, plays a crucial role in maintaining metabolic homeostasis. In recent years, growing evidence has highlighted the significant influence of gut microbiota on glucose metabolism, insulin sensitivity, and the pathogenesis of metabolic disorders such as diabetes mellitus.

Alterations in the composition and function of gut microbiota, commonly referred to as dysbiosis, have been strongly associated with the development of insulin resistance and chronic low-grade inflammation. These changes disrupt metabolic signaling pathways, thereby contributing to impaired glycaemic control. Consequently, the gut microbiota has emerged as a key target in the management of diabetes (Tilg & Moschen, 2014).

2. Composition and Functions of Gut Microbiota

The gut microbiota is predominantly composed of bacterial phyla such as Firmicutes, Bacteroidetes, Actinobacteria, and Proteobacteria. These microorganisms perform essential physiological functions, including digestion of dietary components, synthesis of vitamins, regulation of immune responses, and maintenance of gut barrier integrity.

One of the most important functions of gut microbiota is the fermentation of non-digestible dietary components, particularly dietary fiber, resulting in the production of short-chain fatty acids (SCFAs) such as acetate, propionate, and butyrate. These metabolites play a central role in regulating glucose and lipid metabolism, as well as modulating inflammatory responses (Koh et al., 2016).

3. Gut Microbiota and Glucose Metabolism

The gut microbiota influences glucose metabolism through multiple interconnected mechanisms. SCFAs produced during microbial fermentation enhance insulin sensitivity by activating specific receptors such as G-protein-coupled receptors (GPR41 and GPR43). These pathways improve glucose uptake and reduce hepatic glucose production.

Additionally, gut microbiota regulates the secretion of incretin hormones, including glucagon-like peptide-1 (GLP-1), which enhances insulin secretion and improves glycaemic control. The modulation of bile acid metabolism by gut microbes further influences glucose homeostasis through signaling pathways involving the farnesoid X receptor (FXR) (Koh et al., 2016).

Gut Microbiota Components and Their Role in Glycaemic Regulation

Component	Source/Origin	Mechanism of Action	Effect on Diabetes
Short-chain fatty acids (SCFAs)	Fiber fermentation	Activates GPR41/43, improves insulin sensitivity	Enhances glucose metabolism
Bifidobacteria	Prebiotic-rich diet	Improves gut barrier, reduces inflammation	Reduces insulin resistance
Lactobacillus	Fermented foods	Modulates microbiota composition	Improves glycaemic control
Lipopolysaccharides (LPS)	Gram-negative bacteria	Triggers inflammation	Increases insulin resistance
Bile acids (modified by microbiota)	Gut metabolism	Regulates FXR signaling	Influences glucose homeostasis

4. Dysbiosis and Insulin Resistance

Dysbiosis is characterized by an imbalance in microbial composition, often involving a reduction in beneficial bacteria and an increase in pathogenic species. This imbalance contributes to metabolic dysfunction through several mechanisms.

One of the key pathways involves increased intestinal permeability, commonly referred to as "leaky gut," which allows lipopolysaccharides (LPS) from gram-negative bacteria to enter the systemic circulation. This triggers chronic low-grade inflammation, a condition known as metabolic endotoxemia, which is strongly associated with insulin resistance (Tilg & Moschen, 2014).

Furthermore, dysbiosis alters SCFA production and disrupts hormonal signalling, leading to impaired glucose regulation and increased risk of type 2 diabetes.

5. Role of Dietary Factors in Modulating Gut Microbiota

Diet is one of the most influential factors shaping gut microbiota composition. Dietary patterns rich in fiber, whole grains, fruits, and vegetables promote the growth of beneficial bacteria, while diets high in refined sugars and saturated fats contribute to dysbiosis.

Prebiotic foods, which contain non-digestible carbohydrates, selectively stimulate the growth of beneficial microorganisms such as Bifidobacteria and Lactobacilli. These bacteria enhance SCFA production and improve gut barrier function.

Probiotic foods, including fermented products such as yogurt and kefir, introduce beneficial microorganisms into the gut, thereby restoring microbial balance. These dietary interventions have been associated with improved insulin sensitivity and reduced inflammation (Gibson et al., 2017).

Role of Gut Microbiota in Glycaemic Control

Dietary Fiber / Prebiotics

↓

Gut Microbiota Modulation

↓

SCFA Production (Butyrate, Propionate)

↓

Improved Gut Barrier Function

↓

Reduced Inflammation (↓ LPS)

↓

Improved Insulin Sensitivity

↓

Better Glycaemic Control

6. Clinical Evidence Linking Gut Microbiota and Diabetes

A growing body of clinical and experimental evidence supports the role of gut microbiota in diabetes management. Studies have demonstrated that individuals with type 2 diabetes exhibit distinct microbial profiles compared to healthy individuals, characterized by reduced microbial diversity and altered composition.

Intervention studies have shown that dietary modulation of gut microbiota can lead to improvements in glycaemic control. Increased intake of dietary fiber and prebiotics has been associated with enhanced SCFA production and improved insulin sensitivity.

Additionally, probiotic supplementation has shown promising results in reducing fasting blood glucose and HbA1c levels, although the magnitude of these effects varies across studies. Despite these findings, further large-scale, long-term studies are required to establish definitive clinical recommendations.

7. Therapeutic Implications and Future Perspectives

The modulation of gut microbiota represents a promising therapeutic strategy in diabetes management. Approaches such as dietary interventions, probiotic and prebiotic supplementation, and fecal microbiota transplantation (FMT) are being explored for their potential benefits.

Personalized nutrition, based on individual microbiome profiles, is an emerging area of research that aims to optimize dietary interventions for improved metabolic outcomes. Advances in microbiome research and technology are expected to enhance our understanding of host–microbe interactions and their role in disease management.

8. Integration into Diabetes Management

The role of gut microbiota should be considered within the broader framework of diabetes management. Nutritional strategies that promote a healthy microbiome complement other interventions, including medical nutrition therapy and lifestyle modification.

Integrating microbiome-focused approaches into routine clinical practice requires interdisciplinary collaboration and increased awareness among healthcare professionals. Patient education on the importance of dietary patterns in shaping gut health is essential for effective implementation.

9. Conclusion

Gut microbiota plays a critical role in regulating glucose metabolism and insulin sensitivity, making it a key factor in the pathogenesis and management of diabetes. Dysbiosis contributes to metabolic dysfunction, while targeted dietary interventions can restore microbial balance and improve glycaemic control.

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Medicinal Plants in Diabetes Management: Phytochemistry, Mechanisms, and Applications

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ABSTRACT: Diabetes mellitus is a metabolic disease which affects hundreds of millions of patients and is a substantial burden to the healthcare systems of the world. Although modern pharmaceutical drugs offer a significant amount of glycemic control, their high price, adverse effects, and low availability in resource-restrained environments prompt the need to look into other therapeutic options, and especially into traditional and complementary medicine systems. This chapter is a thorough discussion of medicinal plants associated with the management of diabetes by various traditional medicine system, synthesizing the evidence available on the phytochemical constituents, mechanisms of antidiabetic action postulated, and the practical means of application. Medicinal plants, such as *Trigonella foenum-graecum*, *Momordica charantia*, *Cinnamomum cassia*, *Ocimum sanctum*, and *Allium sativum* combat diabetes in several ways, such as enhancing pancreatic beta-cell activity and insulin release, promoting peripheral insulin receptivity, regulating hepatic glucose production, inhibiting carbohydrate-digesting enzymes, alleviating oxidative stress and inflammation, and facilitating active glucose uptake. The conventional methods of application, like decoctions, infusions, powders, and aqueous extracts, as well as recent extraction methods has been address. Integration of herbal therapeutic practices based on evidence and conventional approaches to diabetes management can be a new paradigm in integrative medicine that promises to improve glycemic control and reduce the pharmaceutical burden and its side effects.

Keywords: Diabetes, phytotherapy, antidiabetic, ethnopharmacology, herbal medicine

1. INTRODUCTION:

Diabetes mellitus has become one of the most urgent health issues of modern medicine. According to the International Diabetes Federation, about 537 million adults worldwide live with diabetes, and this number is projected to rise to 783 million by 2045 unless significant preventive measures are introduced (Yameny, 2024). The economic cost of diabetes to the global economy per year is over 966 billion U.S. dollars and includes all three components, viz., direct healthcare spending, lost productivity, and premature death (Rodriguez-Saldana, 2023). In addition to these epidemiological and economic facts, diabetes is a core cause of morbidity and mortality due to its associated complications that include cardiovascular disease, nephropathy, retinopathy, neuropathy and poor wound healing (Parameswari *et al*., 2025).

Present-day pharmaceutical solutions for diabetes management are effective, but with high glycemic control, are substantially limited. Although insulin treatment is necessary for patients with type 1 diabetes and much of the other severe type 2 diabetes, the medication must be administered parenterally, has a risk of causing hypoglycemic events, and exhibits unreliable absorption properties. Oral antidiabetic drugs, such as sulfonylureas, meglitinides, thiazolidinediones, dipeptidyl peptidase-4 inhibitors, and glucagon-like peptide-1 receptor agonists, are associated with significant adverse effects in patients, including gastrointestinal adverse effects, hepatotoxicity, pancreatitis, and cardiovascular risk in some groups (Khan, 2024). Moreover, the increasing cost price of modern antidiabetic drugs are still repressive even to people in developing and under developed countries where the prevalence of diabetes is growing at a faster pace.

At the same time, research is ongoing investigating the antidiabetic properties of medicinal plants used in folk and official traditional medicine, such as Ayurveda, Traditional Chinese Medicine, and Unani medicine. These herbal extracts, which have been used from ancient times to treat diabetes mellitus, are composed of a variety of phytochemical compounds that interact in complementary ways with current pharmaceutical compounds. The combination of evidence-based herbal medicine treatment with mainstream diabetes management has become a new approach in the field of integrative medicine, promising synergistic benefits in glycemic control and reducing the pharmaceutical load, drug side effects, and treatment costs. In this chapter medicinal plants used in the management of diabetes, their phytochemical components, mechanisms of antidiabetic action, modes of application, and clinical efficacy has been discussed.

PATHOPHYSIOLOGY OF DIABETES:

Diabetes mellitus is a hyperglycemia related metabolic condition, which is caused by several factors including insulin deficiency, defective insulin secretion, insulin resistance, or a combination of these effects (Jadon *et al*., 2024). About 5-10% of diabetes cases is due to Type I diabetes, which is caused by the autoimmune destruction of pancreatic beta cells. This leads to severe insulin deficiency, and the insulin replacement therapy is invaluable in the patient's survival (Green *et al*., 2021). Type 2 diabetes comprises about 90% of all diabetes cases and occurs due to progressive pancreatic beta-cell dysfunction that occurs over a background of insulin resistance (Galicia-Garcia *et al*., 2020). Gestational diabetes, which is acquired in the context of pregnancy and whose pathogenesis is more or less similar to that of type 2 diabetes, predisposes a woman considerably to the development of diabetes in the woman and her child (Plows *et al*., 2018).

Type 2 diabetes pathophysiology involves the multifaceted interaction of multiple organ systems and metabolic processes. As a response to decreased insulin sensitivity, pancreatic beta cells increase insulin secretion, which sustains normoglycemia through pancreatic hyperinsulinemia (Bergman, 2024). But over the years, progressive beta-cell dysfunction develops, in part mediated by mechanisms involving amyloid-beta deposits, endoplasmic reticulum stress, mitochondrial dysfunction, and chronic inflammation (Veselov *et al*., 2023). At the same time, hepatic glucose production becomes pathologically elevated due to the suppression of gluconeogenesis and glycogenolysis by insulin. There is reduced insulin-stimulated glucose uptake in skeletal muscle and adipose tissue dysfunction, with increased lipolysis, decreased adiponectin release, and increased production of inflammatory cytokines (Nicholson *et al*., 2018).

3. METABOLIC TARGETS FOR HERBAL ANTIDIABETIC:

Medicinal plants used to treat diabetes work through several different metabolic processes. Improvement in pancreatic beta-cell functionality is a key goal, and phytochemicals can enhance insulin secretion under basal and stimulated conditions. Another key mechanism is the peripheral insulin sensitivity, which is enhanced, specifically in the skeletal muscle and adipose tissue, by the activation of the components of the insulin signaling cascade. Hepatic glucose production is inhibited by the modulation of the hepatic glucose production due to suppression of gluconeogenic enzymes activity (Zhang *et al*., 2019). Inhibition of carbohydrate digesting enzymes such as alpha-amylase and alpha-glucosidase delays the uptake of glucose after a meal and regulates post meal glycemic outbursts. Antioxidant mediated reduction of oxidative stress and inhibition of inflammation by inhibition of pro-inflammatory cytokines targets the etiological pathogenesis involving which beta-cells dysfunction and causes insulin resistance (Hu *et al*., 2022). Glycemic control is enhanced by direct facilitation of glucose uptake in peripheral tissues, especially by promoting GLUT4 translocation (Sylow *et al*., 2017). Also, some of the plants are able to regulate lipid metabolism, which decreases dyslipidemia and related hepatic steatosis, which worsen insulin resistance (Hu *et al*., 2022).

4. MAJOR MEDICINAL PLANTS USED FOR DIABETES MANAGEMENT:

Several medicinal plants with antidiabetic properties have been used in traditional healthcare systems and subjected to scientific validation. The following sections will discuss important plants that have been shown to have antidiabetic effects, along with detailed information about their active ingredients and how they are traditionally and currently used.

4.1 Trigonella foenum-graecum (Fenugreek):

Trigonella foenum-graecum is one of the widely explored medicinal plants for the management of diabetes. This plant is rich in several bioactive compounds, such as alkaloid trigonelline, saponins, flavonoids, and soluble fibre galactomannan (Niknam *et al*., 2021). Galactomannan fraction, which makes up about 40-50% of the seed mass, exhibits a significant ability to slow down the absorption of carbohydrates as well as regulate the postprandial glucose surges (Urooj *et al*., 2025). Trigonelline is known to have direct action on pancreatic beta cells and was found to stimulate insulin release *in vitro* and *in vivo* by regulating intracellular Ca^{2+} dynamics and activating insulin secretion-related kinase pathways (Nguyen *et al*., 2024). This plant has been clinically proven to possess high antidiabetic properties. Randomised controlled trials with doses of 5-15 grams of fenugreek seeds or seed powder daily have reported a 25-35% reduction in fasting blood glucose and a 0.5-1.2% reduction in haemoglobin A1C, which is in the range of 0.5-12% in some pharmaceutical agents (Chehregosha *et al*., 2025). The mechanisms are alpha-glucosidase inhibition by polyphenolic compounds, stimulation of glucose uptake in skeletal muscle by insulin via enhanced GLUT4 translocation, and regulation of hepatic glucose metabolism. Also, fenugreek has shown positive lipid metabolic properties, which decrease the level of triglycerides and increase the high-density lipoprotein cholesterol (Heshmat-Ghahdarijani *et al*., 2020).

4.2 *Momordica charantia* (Bitter Melon):

Momordica charantia is used in traditional Asian medicinal practice to treat diabetes. It contains several bioactive compounds, such as polypeptides-p; momordicin alkaloids; and a variety of phenolic compounds. Polypeptide-p exhibits the ability to reduce blood glucose by both direct stimulation of pancreatic beta cells and increasing the absorption of glucose in the peripheral tissues (Elbakry & Elremaly, 2023). Also, bitter melon has hepatic gluconeogenesis inhibitory compounds and insulin sensitivity enhancing compounds by activating phosphoinositide 3-kinase/Akt signalling cascades (Zhou & Xu, 2023). Human clinical trials on bitter melon administration normally use fresh juice, powdered dried or aqueous extracts with doses of 50-200 mL daily or equivalent, with fasting glucose reductions of 10-25% and postprandial glucose reductions of 15-35% (Jane-Frances & Chichaya, 2023). The plant has several antidiabetic effects, such as reducing glucose absorption by inhibiting intestinal glucose transporters, improving cellular glucose metabolism through activation of AMP-activated protein kinase, and increasing glucagon-like peptide-1 secretion. Interestingly, bitter melon shows improved efficacy when co-administered with traditional antidiabetic agents, suggesting the possibility of synergistic therapy.

4.3 Cinnamomum cassia and Cinnamomum verum (Cinnamon):

Cinnamon is a product of a *Cinnamomum cassia* or *Cinnamomum verum* obtained from the bark, and is one of the most thoroughly studied spices in metabolic actions. Methylhydroxychalcone polymer (MHCP) and other polyphenolic compounds are the active compounds which increase insulin signaling by activating the insulin receptor tyrosine kinase, insulin translocation into GLUT4 in muscles and adipose tissue, and blocking protein tyrosine phosphatase 1B, a negative regulator of insulin signaling (Haldar *et al*., 2022). Also, cinnamon and its effects have potent antioxidant and anti-inflammatory properties due to their ability to inhibit the activation of nuclear factor-kappa B. Clinical trials involving 1–6 grams of cinnamon per day show fasting glucose decreases of 10-29% in patients with type 2 diabetes and hemoglobin A1C decreases of 0.48-1.04% (Kizilaslan & Erdem, 2019). Notably, these effects occur without any alterations in insulin levels, implying that they are independent of insulin. Cinnamon also exhibits positive lipidic actions, which lower the levels of triglyceride and overall cholesterol while raising high-density lipoprotein cholesterol. The spice has a very good safety profile and tolerability, and can be administered long term without many side effects, except for occasional gastrointestinal symptoms.

4.4 *Ocimum sanctum* (Holy Basil/Tulsi):

Ocimum sanctum is an Ayurvedic medicinal plant that has been described with an antidiabetic effect. The plant contains wide range of phytochemicals, such as eugenol, linalool, estragole, methyl cinnamate, and many polyphenolic compounds. These substances improve insulin secretion, pancreatic beta-cell activity, peripheral insulin sensitivity, and reduce oxidative stress through both enzymatic and non-enzymatic antioxidant activities (Vijay *et al*., 2025). The use of dried leaf powder and aqueous leaf extracts effectively decrease 17-21% and 18-26% in fasting and postprandial glucose, respectively, in type 2 diabetes individuals (Olofinsan *et al*., 2024). But these effects appear over several weeks of administration, indicating the formation of physiological accommodation rather than acute drug effects. Holy basil has shown a specifically high degree of stress-reducing properties by regulating cortisol secretion, which alleviates stress-induced hyperglycemia and metabolic imbalance. The plant shows very high safety and tolerability, with few adverse effects, including occasional mild gastrointestinal effects.

4.5 *Allium sativum* (Garlic):

Allium sativum contains many sulfur-based compounds such as allicin, ajoene, and S-allyl cysteine, which have very strong antidiabetic effects. The compounds improve the insulin secretion from pancreatic beta-cells by acting both via the regulation of intracellular calcium signaling and potassium channel interactions (Jain *et al*., 2025). Another effect of the constituents in garlic is that it enhances the peripheral insulin sensitivity and glucose uptake in skeletal muscle by translocation of GLUT4 and inhibition of gluconeogenesis by inhibition of important gluconeogenic enzymes such as phosphoenolpyruvate carboxykinase and glucose-6-phosphatase (Xie *et al*., 2023). It has been shown that clinical studies using 0.5-1.5 grams of raw or processed garlic daily have led to reductions in fasting glucose of 6-15% and reductions in hemoglobin A1C of 0.15-0.42% (Najman *et al*., 2020). It is also worth noting that there are synergies between garlic and some pharmaceutical antidiabetic compounds, which may allow a reduction in the dose of more traditional medicines. In addition to glucose-lowering effects, garlic shows a strong effect in reducing dyslipidemia and hypertension, which often co-exist with diabetes. The mechanism of the antidiabetic effect seems to be the increased insulin secretion, insulin sensitivity, and antioxidant defense of the pancreatic beta cells.

5. TRADITIONAL AND CONTEMPORARY MODES OF APPLICATION:

Methodologies for preparation and routes of administration are paramount to the therapeutic effectiveness of medicinal plants with regard to bioavailability, absorption dynamics, and the amount of bioactive compounds delivered to the systemic circulation. Older methods of preparation have been developed over centuries of practical use and usually represent the most effective means of therapy, with the least complexity and cost of preparation.

5.1 Decoctions:

Decoction is perhaps the oldest of all preparation techniques, especially for plant materials that contain bioactive compounds which are heat-resistant, such as alkaloids, saponins, and polysaccharides. It is done by boiling the plant materials, usually bark, roots, seeds, or dried leaves, in water over long periods of time, ranging between 15-45 minutes, whereby water soluble compounds are extracted and also water is evaporated, thus decreasing the volume. Decoctions have high extraction efficiency for compounds in plant cell walls and for those requiring thermal disruption. For antidiabetic plants, traditional preparations are decoctions of fenugreek seeds, bitter melon, and dried *Ocimum sanctum* leaves. The applicable dose ranges with 100-200 milliliters of decoction 23 times a day, and its effects are likely to be observed in 24 weeks' time (Sahu *et al*., 2026).

5.2 Infusions:

In infusion technique, the boiling step has been eliminated, and the herbs are heated with hot water and left to steep for 10-20 minutes, allowing the extraction of thermolabile compounds such as volatile essential oils, some polyphenols, and sensitive alkaloids. Infusions are especially effective in aerial parts of plants, leaves, flowers, and herbaceous stems, which are more easily treated than woody parts of plants. Infusions often use holy basil leaves, pieces of cinnamon sticks, and fenugreek seeds as ingredients to help manage diabetes. The liquid that follows retains the typical flavors and aromas of plants and improves the palatability and compliance of the user. Common dosing is 1 cup of infusion, taken 2 times a day, with the preparation made by steeping 1-2 teaspoons of the dried plant matter in 200-250 milliliters of hot water (Alamgir, 2017).

5.3 Powder and Capsule Forms:

Simple and stable preparations that are best for long term storage and are easily administered can be represented by powders formed by the process of grinding dry plant constituents into fine particles. The powdered form exhibits a longer shelf life than fresh preparations or liquid extracts, and little degradation of bioactive compounds occurs with the powdered form when kept in cool and dry environments and free of direct exposure to light. Powders can be taken with water, combined with food or put into capsules to be taken easily orally. In the use of antidiabetic treatment, fenugreek seeds, cinnamon bark and dried holy basil powders are effective and consistent in clinical research. The standard dose is 2-10 grams in a day, often in two or three doses with therapy often being administered with meals to maximize interactions with digestive processes in the locality and to enhance glucose control (Evert *et al*., 2014).

5.4 Aqueous and Hydroalcoholic Extracts:

To date, extraction approaches allow selective recovery of individual phytochemical fractions, thereby increasing the concentration of bioactive compounds and therapeutic effects. Aqueous extracts, water extracts made by moistening the dry plant material in water, and concentration by means of evaporation, retain aqueous soluble compounds, but remove lipophilic compounds. Hydroalcoholic extracts that are made using a mixture of ethanol or methanol and water yield more dramatic levels of hydrophilic and lipophilic compound and consequently show a broader spectrum of phytochemicals. With standardized extracts, which provide known quantities of known active compounds, it is possible to administer the correct dosage and give reproducible results. In managing diabetes, the efficacy of standardized extracts of bitter melon, cinnamon, and fenugreek is very high at adosage of 250-1000 milligrams per day in portions, which are taken in together with food (Manhas *et al*., 2025).The apparent efficacy of the hydroalcoholic extracts prepared using ethanol or methanol and water mixtures gives higher concentrations of hydrophilic and lipophilic compounds and therefore a broad range of phytochemicals. With standardized extracts, which provide known quantities of active compounds, it is possible to administer the correct dosage and give reproducible results. Standardized extracts of bitter melon, cinnamon, and fenugreek have very high efficacy at the dosage of 250-1000 milligrams per day divided into portions and administered with meals in the treatment of diabetes (Manhas *et al*., 2025).

6. MECHANISMS OF ANTIDIABETIC ACTION AND CLINICAL EFFICACY:

The medicinal plants are used to combat diabetes pathophysiology in a combination of mechanisms which targets underlying disease pathways. The modern perspective on these processes is the result of active research on these processes using both cellular and molecular methods of biochemical research and animal models of diabetes, as well as the clinical studies of people.

6.1 Enhancement of Pancreatic Beta-Cell Function:

One of the principal modes in which herbal antidiabetic agents exert therapeutic effects is by enhancing pancreatic beta-cell function and stimulating insulin secretion. Lots of phytochemicals directly enhance insulin secretion by means of calmodulation of intracellular calcium activity, activation of suture of sulfonylurea receptor independent potassium channels, and increasing insulin sensitivity to glucose (Wang *et al*., 2021). Besides, phytochemicals help prevent apoptotic degeneration of beta cells by acting as antioxidants and inhibiting pro-inflammatory cytokine signaling. Plant-derived compounds such as polyphenols, alkaloids, and polysaccharides exhibit the ability to restore functionally impaired beta cells, and make them functional again to release glucose responsive insulin secretions. This preventive effect on beta-cells is especially important, given that progressive beta-cell dysfunction is a fundamental feature of type 2 diabetes pathogenesis.

6.2 Improvement of Peripheral Insulin Sensitivity:

Second, a significant improvement in peripheral insulin sensitivity is a second way medicinal plants can be used to enhance diabetic control. Phytochemicals stimulate insulin signaling pathways in skeletal muscle and adipose tissue to stimulate glucose uptake by GLUT4 translocation and increase intracellular glucose metabolism by activating glycolytic enzymes (Sayem *et al*., 2018). Also, the herbal compounds enhance adipocyte activity, which mediates proper adiponectin release, lessen hepatic steatosis, and reduce systemic inflammation. By increasing the activity of the AMP-activated protein kinase using phytochemical compounds, it has been found to increase the function of the mitochondria in muscle and adipose tissue, which increases the cells' metabolism of glucose and lowers inflammatory signaling. Hepatic glucose production is decreased by enhancing hepatic insulin sensitivity, thereby treating a pathophysiological abnormality in type 2 diabetes.

6.3 Inhibition of Carbohydrate-Digesting Enzymes:

Polyphenolic compounds present in many medicinal plants have the ability to inhibit alpha-amylase and alpha-glucosidase enzymes that hydrolyze the carbohydrates in the diet. This enzyme inhibition slows down the process of carbohydrate digestion and glucose absorption, thereby moderating postprandial glucose levels. Compared with pharmaceutical alpha-glucosidase inhibitors, which often cause serious gastrointestinal adverse effects due to excessive delivery of undigested carbohydrates to the colon, the low-level enzyme inhibition caused by herbal compounds leads to acceptable, and in most cases, therapeutically promising, postprandial glucose responses. The resulting slight increase in colonic carbohydrates enhances the growth of beneficial microorganisms and production of short-chain fatty acids, which may increase insulin sensitivity and metabolic fitness by other mechanisms.

7. INTEGRATION OF HERBAL THERAPEUTICS AND CONVENTIONAL DIABETES MANAGEMENT:

Evidence-based herbal treatment with conventional pharmaceutical management of diabetes is a new paradigm of integrative medicine. Instead of presenting herbal medicine and pharmaceuticals as alternative practices, modern practice focuses on their complementary potential to achieve optimal glycemic control with the fewest adverse effects and treatment burden. Such a combined practice must be closely monitored, patient selection must be appropriately matched, and possible interactions between herbal compounds and pharmaceutical agents must be considered.

It is becoming apparent that medicinal plants are able to augment the effectiveness of conventional antidiabetic agents and reduce the dosage of pharmaceutical drugs. For example, co-administration of metformin with fenugreek has better glycemic control than either alone, and may allow the metformin dose to be reduced, thereby reducing gastrointestinal side effects. Equally, bitter melon supplementation could lead to an amplification of the glucose-lowering effect of sulfonylureas, and good glucose monitoring must be implemented to prevent hypoglycemia. Holy basil exhibits a synergistic effect with many antidiabetic agents, improving their effectiveness and reducing the risk of adverse effects. Such a reciprocal association is very likely to reflect the multi-synergistic, compound effects of herbal medicines on diabetes pathophysiology, which add to the more specific physiological actions of pharmaceutical agents.

Integrative diabetes management implementation needs special care in terms of the possibility of drug-herb interaction. Some medicinal plants change hepatic metabolism of drugs by causing cytochrome P450 enzyme modulation and may decrease pharmaceutical bioavailability or raise the concentration of toxic levels in circulation. Practitioners who utilize integrative methodologies need to be mindful of such interactions and carry out due diligence on pharmaceutical-herb interactions and modify the dosage of pharmaceuticals accordingly when the patient receives herbal therapies. Moreover, herbal drugs can increase the likelihood of hypoglycemia with pharmaceutical agents, so the glucose level should be observed more closely and the pharmaceutical dosage should be reduced. Herbal therapeutics and conventional management of diabetes, integrated with proper precautions and care, hold immense potential for better results, lesser pharmaceutical load, and better quality of life for patients.

8. SAFETY PROFILE AND ADVERSE EFFECTS:

When used properly, in appropriate amounts and dosages, medicinal plants usually show very good safety profiles and little to no side effects as compared to conventional pharmaceutical based agents. Nevertheless, as with any treatment agent, identifying potential side effects and contraindications is necessary. The most frequent category of adverse effects is gastrointestinal, with some plants such as bitter melon and fenugreek known to cause nausea, diarrhea, and stomach pain, especially with high doses or when used without food. Such effects are common when further administrations reduce them as gastrointestinal adaptation takes place.

Hypoglycemia is a potential severe side effect when herbal antidiabetic drugs are used with pharmaceutical drugs without proper dose modification or glucose monitoring. Patients undergoing insulin or sulfonylureas therapy must be especially careful when starting herbal antidiabetic therapy, and have an increased rate of glucose monitoring and pharmaceutical dose reduction. Pregnant women should be excluded from the treatment with most antidiabetic herbal medications since the reproductive safety of most medicinal plants is not yet fully defined. Also, patients who have some of the medical conditions, such as severe hepatic or renal impairment, should be given close consideration before herbal antidiabetic therapy is started. Although herb-drug interactions with medicinal plants are generally moderate with the typical usage of these plants in diabetes, in people taking a combination of a few pharmaceutical agents with low therapeutic indexes, these interactions might be clinically relevant.

9. FUTURE DIRECTIONS AND RESEARCH PRIORITIES:

There are still substantial prospects of progress in the field of studying the antidiabetic potential of medicinal plants and streamlining their clinical use. The next approach of studies needs to focus on standardization of the herbal preparations to achieve uniformity in bioactive compounds in batches and formulations, which would facilitate stringent clinical research and provide a consistent therapeutic effect. Greater and increased-period randomized controlled trials between herbal antidiabetic agents and pharmaceutical standards and usage in combined therapeutic modalities should be looked into. Mechanistic experiments on high-technology molecular methodologies, such as transcriptomic and proteomic studies, will shed light on the overall impact of herbal compounds on metabolism, which may reveal new therapeutic opportunities. Research into the traditional preparation procedures and optimization of the latter by means of modern technological solutions can lead to the improvement of the treatment outcomes without relying on resources that are not always accessible in similarly limited resources. Moreover, analysis of combination strategies of several medicinal plants with complementary effects is a field of high potential, as it may potentially result in greater therapeutic outcomes because of synergistic activities of various phytochemicals.

9. CONCLUSION:

Being one of the commonly widespread metabolic diseases, diabetes mellitus requires holistic treatment solutions that target a variety of pathogenic processes. The medicinal plants, advanced and enhanced in the practice of traditional medicine over centuries, and more and more justified by the strict scientific research, are the beneficial sources of treatment of the diabetes pathophysiology. The plants featured in this chapter, such as *Trigonella foenum-graecum*, *Momordica charantia*, *Cinnamomum* species, *Ocimum sanctum*, and *Allium sativum*, among manyothers, are shown to have significant antidiabetic activity due to various, complementary mechanisms such as benefiting the pancreatic beta-cells, improving peripheral insulin sensitivity, modulating hepatic glucose production, preventing carbohydrate digestion, and reducing oxidative stress and inflammation. Older application methods, such as decoctions, infusions, powders, and modern standardized extracts, give practitioners the choice of flexibility in delivery of herbal medicine, having the option to optimize based on patient preferences, clinical situation, and available resources. Combining evidence-based herbal therapeutic interventions with traditional forms of diabetes care, by the use of cautious clinical monitoring and proper patient selection, has a great potential of improving glycemic control, decreasing pharmaceutical load, limiting adverse effects, and improving patient quality of life. Due to the growing limitations of the traditional mode of treatment by antimicrobial resistance and the side effects of excessive drug use, medicinal plants are available to provide convenient, affordable treatment options worldwide, especially in those areas where the supply of pharmaceuticals is limited and where the traditional mode of treatment is constrained. The meeting of common medicine expertise with the modern scientific corroboration renders medicinal plants to the core of the upcoming diabetes management techniques, and so the hope of hundreds of millions of people around the globe currently afflicted with this chronic metabolic illness.

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Nutrition and Lifestyle Interventions in Diabetes Management: From Diet Therapy to Gut Health

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Abstract

Diabetes mellitus is a complex metabolic disorder requiring comprehensive management strategies beyond pharmacological treatment. Nutrition and lifestyle interventions remain the cornerstone of effective diabetes care, playing a pivotal role in glycaemic control, prevention of complications, and improvement of overall quality of life. This chapter explores evidence-based nutritional and lifestyle approaches for diabetes management, emphasizing the transition from conventional diet therapy to emerging insights into gut health. The chapter begins with an overview of Medical Nutrition Therapy (MNT), highlighting individualized meal planning, macronutrient distribution, glycemic index and load, and the role of dietary fiber in regulating blood glucose levels. The importance of functional foods, micronutrients and nutraceuticals in enhancing insulin sensitivity and reducing inflammation is also discussed. Lifestyle components such as regular physical activity, yoga, stress management and behavioral modifications are examined for their synergistic effects on metabolic control. A significant focus is placed on the role of gut microbiota in glucose metabolism and insulin resistance. Practical dietary strategies aimed at promoting gut health are outlined , along with their implications for long term diabetes management. By integrating nutritional science with lifestyle medicine and emerging gut health research, this chapter provides a holistic framework for diabetes management. The content is

intended to support healthcare professionals, nutritionists, researchers and students by offering practical, preventive, and sustainable strategies that align with current public health and clinical nutrition guidelines.

Keywords: Diabetes management; Medical Nutrition Therapy; Lifestyle intervention; Functional foods; Gut microbiota; Glycemic Control

1. Introduction

1.1 Global burden of Diabetes

Diabetes mellitus has become a critical public health concern worldwide, impacting populations in both high-income and low-income countries. Recent estimates from the International Diabetes Federation indicates that nearly 537 million adults were affected by diabetes globally in 2021, with projections suggesting a continued and substantial rise in prevalence in the coming years (International Diabetes Federation [IDF], 2021). The World Health Organization (WHO) identifies diabetes as a leading contributor to illness and premature death, largely due to its association with cardiovascular complications, renal dysfunction, neuropathic disorders, and vision loss (World Health Organization [WHO], 2023). Factors such as rapid urban growth, shifts toward energy-dense diets, and reduced physical activity have significantly fueled the increasing incidence of type 2 diabetes, particularly in low- and middle-income regions.

1.2 Need for Integrated Nutrition and Lifestyle Strategies

While pharmacological therapies remain a cornerstone of diabetes treatment, effective long-term management depends on the adoption of comprehensive lifestyle-based approaches. Research demonstrates that appropriate dietary practices, regular physical activity, stress reduction, and sufficient sleep are essential for enhancing insulin sensitivity and maintaining optimal glycemic levels (American Diabetes Association [ADA], 2024). Nutritional patterns emphasizing whole grains, legumes, fruits, vegetables, and fiber-rich foods contribute not only to improved metabolic outcomes but also to dietary sustainability and greater long-term compliance (FAO & WHO, 2019; Willett et al., 2019). Consequently, the integration of nutrition and lifestyle interventions offers a holistic and sustainable framework for both the prevention and management of diabetes.

1.3 Scope and Objectives of the Chapter

The purpose of this chapter is to examine the contribution of sustainable nutritional practices and lifestyle modifications to effective diabetes management. It focuses on sustainable dietary models, functional and bioactive foods, gut health, physical activity, and community-level preventive initiatives. In addition, the chapter discusses how these strategies align with broader public health priorities and the Sustainable Development Goals. By combining scientific evidence with culturally sensitive and environmentally conscious practices, this chapter presents a comprehensive approach to promoting sustainable diabetes care.

2. Overview of Diabetes and Metabolic Dysregulation

2.1 Pathophysiology of Diabetes

Diabetes mellitus is a complex metabolic disorder characterized by chronic hyperglycaemia resulting from impaired insulin secretion, insulin action, or both. In type 1 diabetes, autoimmune destruction of pancreatic β-cells leads to absolute insulin deficiency. In contrast, type 2 diabetes, which accounts for the majority of cases, involves a combination of insulin resistance and progressive β-cell dysfunction (American Diabetes Association [ADA], 2024). Persistent hyperglycaemia disrupts carbohydrate, fat, and protein metabolism, leading to long-term complications affecting the cardiovascular system, kidneys, nerves, and eyes (World Health Organization [WHO], 2023).

2.2 Role of Insulin Resistance and Inflammation

Insulin resistance is a key feature in the development of type 2 diabetes, where peripheral tissues such as skeletal muscles, liver, and adipose tissue show reduced responsiveness to insulin. This leads to impaired glucose uptake and increased hepatic glucose production. Chronic low-grade inflammation is closely associated with insulin resistance and metabolic dysregulation. Adipose tissue dysfunction results in the release of pro-inflammatory cytokines, oxidative stress, and altered adipokine secretion, which further impair insulin signaling pathways (Canfora et al., 2019; DeFronzo et al., 2015). These metabolic disturbances contribute to disease progression and increase the risk of cardiovascular complications.

2.3 Lifestyle Factors Influencing Disease Progression

Lifestyle factors play a significant role in the onset and progression of diabetes. Diets high in refined carbohydrates, saturated fats, and ultra-processed foods contribute to obesity, inflammation, and insulin resistance. Physical inactivity and sedentary behavior further worsen metabolic health and glycemic control (International Diabetes Federation [IDF], 2021). Additionally, chronic stress, poor sleep quality, and unhealthy behavioral patterns negatively influence hormonal balance and glucose metabolism. Adoption of healthy dietary patterns, regular physical activity, stress management, and adequate sleep can slow disease progression and improve overall metabolic outcomes (ADA, 2024).

3. Medical Nutrition Therapy (MNT) in Diabetes Management

3.1 Principles and Goals of MNT

Medical Nutrition Therapy (MNT) is a cornerstone in the prevention and management of diabetes mellitus. It focuses on optimizing glycaemic control, improving metabolic outcomes, and preventing diabetes-related complications through planned dietary interventions. The primary goals of MNT include maintaining blood glucose levels within target range, achieving healthy body weight, improving lipid profile, and controlling blood pressure. Medical Nutrition Therapy also aims to promote sustainable and culturally acceptable dietary patterns that enhance long-term adherence and overall quality of life. Evidence suggests that structured nutrition therapy significantly reduces Glycated haemoglobin (HbA1c) levels and improves insulin sensitivity in individuals with diabetes (American Diabetes Association [ADA], 2024).

3.2 Individualized Meal Planning

Individualization is a fundamental principle of effective MNT. Dietary recommendations should be tailored according to age, sex, physical activity level, socio-economic status, cultural food practices, and comorbid conditions. Personalized meal planning helps improve dietary compliance and supports behavioral modifications essential for diabetes management. Portion control, meal timing, and distribution of carbohydrate intake throughout the day are critical components of individualized plans. Additionally, patient education and counseling play a vital role in promoting self-management skills and sustainable lifestyle changes (Evert et al., 2019).

3.3 Macronutrient Distribution and Energy Balance

Balanced macronutrient intake is essential in diabetes management. Although no universal macronutrient ratio is recommended, carbohydrate intake typically contributes 45–60% of total energy, protein 15–20%, and fats 20–35%, depending on individual needs. Emphasis is placed on complex carbohydrates, lean protein sources, and healthy fats such as monounsaturated and polyunsaturated fatty acids. Maintaining appropriate energy balance supports weight management, which is crucial in improving insulin sensitivity and metabolic regulation (ADA, 2024).

3.4 Glycaemic Index, Glycemic Load, and Carbohydrate Quality

The glycemic index (GI) measures how rapidly carbohydrate-containing foods raise blood glucose levels, while glycemic load (GL) considers both the quality and quantity of carbohydrate intake. Consumption of low-GI and low-GL foods helps reduce postprandial glucose fluctuations and improves overall glycemic control. Whole grains, legumes, fruits, and minimally processed foods are recommended over refined carbohydrates and sugar-rich products. Improving carbohydrate quality is strongly associated with reduced risk of diabetes complications and better metabolic outcomes (Augustin et al., 2015).

3.5 Role of Dietary Fiber in Glycemic Control

Dietary fiber plays a significant role in regulating glucose metabolism and improving insulin sensitivity. Soluble fiber delays gastric emptying, reduces glucose absorption, and enhances satiety, thereby supporting weight management. High-fiber diets have been linked with improved glycemic control, reduced serum cholesterol levels, and decreased cardiovascular risk. Sources such as whole grains, pulses, vegetables, fruits, and millets provide both soluble and insoluble fiber and contribute to sustainable and nutritionally balanced dietary patterns (Reynolds et al., 2020) [see Fig 1].

[Fig 1: Role of Dietary fiber in Diabetes Management]

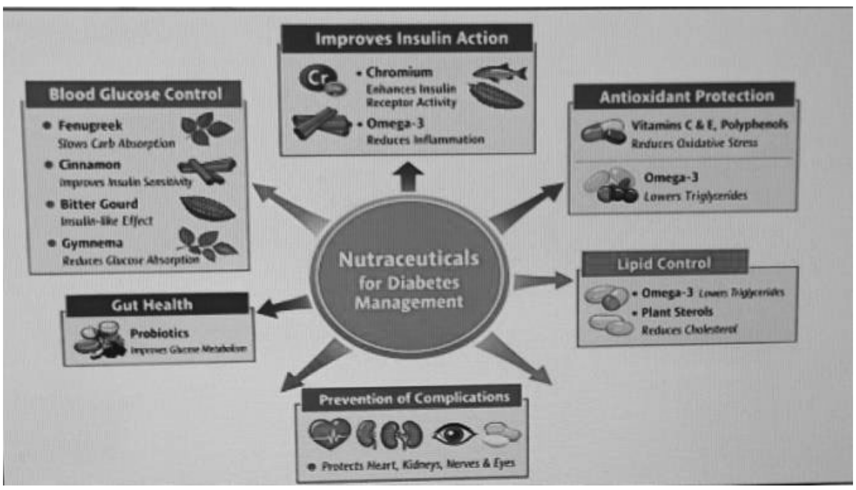
4. Functional Foods, Micronutrients, and Nutraceuticals

4.1 Functional Foods with Antidiabetic Potential

Functional foods are defined as foods that provide health benefits beyond basic nutrition due to the presence of bioactive compounds. Several functional foods have demonstrated antidiabetic properties through mechanisms such as improving insulin sensitivity, reducing oxidative stress, and regulating carbohydrate metabolism. Whole grains, millets, legumes, fermented foods, and plant-based foods rich in polyphenols and antioxidants contribute significantly to glycemic regulation. Foods such as oats, barley, fenugreek seeds, cinnamon, bitter gourd, and flaxseeds have shown potential in reducing postprandial glucose levels and improving metabolic health. Regular consumption of these foods supports sustainable dietary patterns and long-term diabetes management (Augustin et al., 2015; Reynolds et al., 2020).

4.2 Evidence-Based Nutraceuticals and Herbal Components

Nutraceuticals and herbal supplements are increasingly being explored as complementary therapies in diabetes management. Bioactive compounds such as curcumin, berberine, alpha-lipoic acid and omega-3 fatty acids have demonstrated beneficial effects in improving insulin sensitivity and reducing inflammation. Traditional herbal components including fenugreek, cinnamon, bitter gourd, and gymnema have shown promising antidiabetic effects in clinical and experimental studies. These components may help regulate glucose absorption, enhance insulin secretion, and improve lipid metabolism. However, nutraceuticals should be used as adjuncts rather than substitutes for conventional therapy and must be supported by scientific evidence and clinical monitoring (International Diabetes Federation, 2023).



[Fig 2: Role of Nutraceuticals in Diabetes Management]

5. Traditional Diets and Millets

5.1 Role of Traditional Diets in Diabetes Prevention and Management

Traditional dietary patterns have long been recognized for their nutritional adequacy, cultural relevance, and sustainability. Many indigenous diets emphasize whole grains, pulses, seasonal vegetables, fermented foods, and plant-based ingredients, which collectively support metabolic health. Unlike modern dietary patterns characterized by refined carbohydrates, ultra-processed foods, and high sugar intake, traditional diets are typically rich in dietary fiber, micronutrients, and bioactive compounds.

Evidence suggests that traditional dietary practices help regulate postprandial glucose levels, improve insulin sensitivity, and reduce the risk of obesity and metabolic syndrome. These diets also promote balanced macronutrient distribution and encourage mindful eating patterns. Reintroducing traditional food systems is considered a sustainable strategy for long-term diabetes prevention, particularly in developing countries undergoing rapid nutritional transition.

5.2 Nutritional and Functional Importance of Millets

Millets are small-seeded cereal grains widely cultivated in India and other parts of Asia and Africa. Common varieties include finger millet (ragi), pearl millet (bajra), sorghum (jowar), foxtail millet, and little millet. Millets are nutritionally superior to many refined cereal grains due to their high fiber content, low glycemic index, and rich micronutrient profile.

Millets contain significant amounts of calcium, iron, magnesium, and antioxidants that contribute to improved glucose metabolism and metabolic health. Their slow digestibility leads to gradual glucose release, reducing postprandial glycemic spikes. Additionally, millets are gluten-free and suitable for individuals with gluten intolerance. Regular inclusion of millet-based foods has been associated with improved glycemic control, enhanced satiety, and reduced cardiovascular risk.

5.3 Millets as Sustainable and Climate-Resilient Crops

Millets are considered climate-resilient crops due to their ability to grow in arid and semi-arid regions with minimal water requirements. Their cultivation supports biodiversity, soil health, and sustainable agricultural practices. Promoting millet consumption aligns with global sustainability initiatives and supports food security, particularly in resource-limited settings.

From a public health perspective, integrating millets into daily diets provides a dual benefit by addressing both nutritional and environmental sustainability. Government initiatives such as the promotion of millets in national nutrition programs further highlight their importance in combating non-communicable diseases, including diabetes.

5.4 Integration of Traditional Diets and Millets in Diabetes Management

Incorporating millet-based foods such as millet rotis, porridge, upma, and fermented millet preparations into daily meals can improve dietary diversity and metabolic outcomes. Combining millets with pulses, vegetables, and fermented foods enhances nutrient bioavailability and supports gut microbiota health. Educational and community-based interventions promoting traditional diets may improve adherence to sustainable diabetes management strategies.

Table 1 : Nutritional Comparison: Rice vs. Wheat vs. Millets (per 100 g edible portion)

Nutrient	**White Rice**	**Whole Wheat**	**Finger Millet (Ragi)**	**Pearl Millet (Bajra)**	**Foxtail Millet**	**Barnyard Millet**
Energy (kcal)	345	346	336	361	351	307
Carbohydrates (g)	78	71	72	67	60	55
Protein (g)	6.8	11.8	7.3	11.6	12.3	11.2
Fat (g)	0.5	1.5	1.3	5.0	4.3	3.9
Dietary Fiber (g)	0.2-0.5	12.5	11.5	8.5	8.0	10.1
Calcium (mg)	10	30	344	42	31	11
Iron (mg)	0.7	3.5	3.9	8.0	2.8	18.6
Glycemic Index (Approx.)	High (70-77)	Moderate (60-69)	Low-Moderate (54-68)	Low (55)	Low (50-54)	Very Low (41-45)

[Note: Millets have been shown to improve Glycaemic control and metabolic health due to their higher fiber,resistant starch and micronutrient content compared to refined cereals (Saleh et al., 2013; Anitha et al., 2020).**]**

Indian Traditional Diabetes- Friendly Meal Model

A traditional Indian dietary pattern can support diabetes management when meals are balanced, portion-controlled, fiber-rich and based on low-glycaemic foods. This model integrates culturally acceptable foods, sustainable ingredients and glycemic control principles.

Core Principles of the Model

- Emphasis on whole grains and millets
- High dietary fiber intake
- Balanced macronutrient distribution
- Inclusion of seasonal vegetables
- Use of traditional cooking methods
- Limited refined sugar and processed foods

Sample Indian Diabetes- Friendly Daily Meal Chart

Time	**Meal**	**Food Items**	**Nutritional Purpose**
Early morning (6-7 AM)	Metabolic Activation	Warm water with soaked fenugreek seeds / lemon water + 4-5 soaked almonds/ 1 walnut	Improves insulin sensitivity and metabolism
Breakfast (8-9 AM)	Balanced Low-GI Meal	Vegetable oats upma / Ragi dosa with sambar / Moong dal cheela + buttermilk	Provides fiber, protein and sustained energy

Mid-Morning (11 AM)	Micronutrient Snack	Guava / Apple / Papaya / Coconut water	Provides antioxidants and hydration
Lunch (1-2 PM)	Traditional Balanced Thali	1-2 millet rotis / small portion brown rice + Dal / legumes + Seasonal vegetable curry + Salad (cucumber, carrot, tomato) + Curd	Maintains glycemic balance and satiety
Evening Snack (4-5 PM)	Protein- Fiber Snack	Roasted chana / Sprouts salad / Nuts + Green tea / herbal tea	Prevents glucose fluctuation
Dinner (7-8 PM)	Light Low-Carbohydrate Meal	Vegetable millet khichdi / Multigrain roti + leafy vegetable curry / Mixed Vegetable soup with paneer / tofu	Prevents nocturnal glucose spikes
Bedtime (If Needed)	Blood Sugar Stabilization	Warm turmeric milk (low-fat) / small handful of nuts	Prevents night hypoglycemia

This dietary model supports sustainable glycemic control, promotes satiety, enhances gut microbiota and aligns with traditional Indian food systems and sustainable nutrition practices.

6. Lifestyle Interventions for Optimal Glycaemic Control

6.1 Physical Activity and Exercise Recommendations

Regular physical activity is a fundamental component of diabetes management and plays a significant role in improving glycaemic control, insulin sensitivity, and overall metabolic health. Exercise enhances glucose uptake by skeletal muscles through insulin-dependent and insulin-independent pathways. It also supports weight management, reduces cardiovascular risk, and improves lipid metabolism.

Current clinical guidelines recommend at least 150 minutes of moderate-intensity aerobic exercise per week, such as brisk walking, cycling, or swimming, distributed across multiple days. Resistance training involving major muscle groups is also encouraged at least two to three times per week, as it improves muscle mass and insulin responsiveness. Additionally, reducing sedentary behavior, including prolonged sitting, is essential for maintaining metabolic health. Regular physical activity has been consistently associated with improved glycemic control and reduced risk of diabetes-related complications (American Diabetes Association [ADA], 2024).

6.2 Yoga, Stress Management, and Sleep Hygiene

Psychological stress and poor sleep quality are important contributors to metabolic dysregulation and insulin resistance. Chronic stress activates the hypothalamic – pituitary –adrenal axis, leading to increased cortisol secretion, which adversely affects glucose metabolism.

Yoga has emerged as a complementary lifestyle intervention that integrates physical postures, breathing techniques, and meditation. Research indicates that yoga can improve insulin sensitivity, reduce stress hormones, and enhance overall psychological well-being. Regular yoga practice has been associated with improved glycemic parameters and cardiovascular health.

Adequate sleep is another essential factor in diabetes management. Adults are generally recommended to maintain 7–9 hours of quality sleep per night. Sleep deprivation and irregular sleep patterns may impair glucose tolerance, increase appetite-regulating hormone imbalance, and promote weight gain. Therefore, maintaining proper sleep hygiene, including consistent sleep schedules and reduced screen exposure before bedtime, supports metabolic stability and glycemic control (International Diabetes Federation, 2023).

7. Gut Microbiota and Diabetes

7.1 Composition and Functions of Gut Microbiota

The human gastrointestinal tract harbors a complex and dynamic community of microorganisms collectively known as the gut microbiota. These microorganisms include bacteria, viruses, fungi, and archaea that play a crucial role in maintaining metabolic and immune homeostasis. The dominant bacterial phyla in a healthy gut include *Firmicutes*, *Bacteroidetes*, *Actinobacteria*, and *Proteobacteria*.

Gut microbiota contributes to several physiological functions such as digestion of complex carbohydrates, synthesis of vitamins, regulation of immune responses, and production of Short-Chain Fatty Acids (SCFAs) including acetate, propionate, and butyrate. Short-Chain Fatty Acids play an essential role in maintaining intestinal barrier integrity, regulating inflammation, and improving glucose metabolism. Emerging evidence suggests that balanced gut microbiota composition is closely associated with metabolic health and glycemic regulation.

7.2 Gut Dysbiosis and Insulin Resistance

Gut dysbiosis refers to an imbalance in the composition and diversity of intestinal microorganisms, which has been strongly linked to the development of metabolic disorders, including diabetes mellitus. Dysbiosis may increase intestinal permeability, allowing translocation of endotoxins such as lipopolysaccharides into systemic circulation. This process promotes chronic low-grade inflammation, which is a major contributor to insulin resistance and metabolic dysfunction.

Altered gut microbial composition may also impair SCFA production, which negatively affects glucose regulation and energy metabolism. Reduced levels of beneficial bacteria and increased pathogenic microbial species have been associated with obesity, impaired glucose tolerance, and progression of type 2 diabetes. Therefore, maintaining a balanced gut microbial environment is considered an important target for diabetes prevention and management.

7.3 Diet–Microbiota Interactions

Diet is one of the most significant modifiable factors influencing gut microbiota composition. High-fiber diets, plant-based foods, whole grains, pulses, fruits, and vegetables promote the growth of beneficial bacteria and enhance SCFA production, which supports insulin sensitivity and metabolic health. Fermented foods such as yogurt, curd, and traditional fermented cereal-based foods contribute probiotics that help maintain microbial diversity.

In contrast, diets high in refined carbohydrates, saturated fats, and ultra-processed foods may disrupt microbial balance and promote dysbiosis. Increasing consumption of prebiotic-rich foods such as garlic, onion, banana, and whole grains supports the growth of beneficial gut bacteria. Sustainable dietary patterns emphasizing plant diversity and minimally processed foods not only improve gut microbiota composition but also contribute to long-term diabetes management and overall metabolic well-being.

8. Public Health and Preventive Perspectives

Diabetes is a major public health concern worldwide, largely driven by unhealthy dietary habits, sedentary lifestyle, and rising obesity prevalence. Lifestyle-based prevention strategies, including balanced nutrition, regular physical activity, weight management, adequate sleep, and stress control, play a crucial role in reducing diabetes risk and improving metabolic health.

Community and population-level interventions are essential for promoting awareness, early screening, and adoption of healthy behaviors. School and workplace wellness programs, community nutrition education, and promotion of traditional and sustainable dietary practices help improve long-term adherence to preventive strategies. Public infrastructure supporting physical activity, such as parks and walking tracks, also contributes to healthier lifestyles.

Public health nutrition policies are vital for creating supportive food environments. Measures such as food labeling regulations, taxation of sugar-sweetened beverages, and promotion of whole grains, millets, fruits, and vegetables improve dietary quality and reduce metabolic disease risk. Integration of diabetes prevention into national nutrition and non-communicable disease control programs strengthens healthcare delivery and population health outcomes.

9. Future Directions and Emerging Research

Emerging research in diabetes management is increasingly focusing on personalized and technology-driven approaches. Personalized nutrition, guided by genetic, metabolic, and gut microbiome profiling, offers potential for improving glycemic control and treatment adherence. Microbiome-based therapies, including targeted use of probiotics, prebiotics, and synbiotics, are being explored as complementary strategies for improving insulin sensitivity and metabolic regulation.

Digital health technologies such as wearable fitness trackers, mobile health applications, continuous glucose monitoring systems, and telemedicine platforms are transforming diabetes care by enabling real-time monitoring and personalized lifestyle management. These tools support early detection, patient engagement, and improved self-management practices.

Despite these advancements, several research gaps remain, including limited long-term clinical evidence on nutraceuticals and microbiome therapies, variability in individual dietary responses, and challenges related to healthcare accessibility and digital literacy. Future research should emphasize multidisciplinary, culturally appropriate, and sustainable strategies to enhance diabetes prevention and management.

Conclusion

Diabetes mellitus is a multifactorial metabolic disorder requiring comprehensive and long-term management strategies. This chapter highlights the crucial role of medical nutrition therapy, functional foods, lifestyle modification, gut health, and traditional dietary practices in achieving optimal glycemic control and preventing diabetes-related complications. Evidence indicates that balanced diets rich in whole grains, millets, pulses, fruits, vegetables, and fermented foods, along with regular physical activity and behavioral interventions, significantly improve metabolic health outcomes.

Holistic and sustainable approaches are essential for effective diabetes management. Integrating culturally acceptable dietary patterns, promoting plant-based and fiber-rich foods, and encouraging community-based lifestyle interventions support long-term adherence and public health benefits. Additionally, emerging strategies such as personalized nutrition, microbiome-based therapies, and digital health technologies offer promising opportunities for improving diabetes care.

Adopting multidisciplinary, preventive, and sustainability-focused interventions is critical to addressing the growing global burden of diabetes. Future efforts should emphasize evidence-based, culturally relevant, and environmentally sustainable practices to enhance population health and improve quality of life among individuals living with diabetes.

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Wheatgrass (*Triticum aestivum*) as a Bioactive-Rich Nutraceutical for Diabetes Management: Mechanistic and Therapeutic Perspectives

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Abstract: Diabetes mellitus (DM) is a rapidly growing metabolic disease with chronic hyperglycaemia, insulin resistance and associated oxidative stress-mediated complications. Diabetes has become an increasing burden and thus has increased interest in plant-based nutraceuticals as safe and sustainable complementary interventions. Wheatgrass (Triticum aestivum), the young shoot of the wheat plant, has found to be a promising bioactive rich functional food because of its high nutritive and phytochemical values. It is rich in chlorophyll, polyphenols, flavonoids, phenolic acids, vitamins, minerals, enzymes, amino acids and dietary fibre, which are responsible for its antioxidant, anti-inflammatory, hypoglycaemic and insulin sensitizing properties. Wheatgrass has been shown to have beneficial effects on glycaemic control by increasing insulin production, reducing the activity of enzymes that break down carbohydrates, decreasing oxidative stress, and regulating inflammatory pathways. Furthermore, its nutraceutical formulations such as fresh juice, powder, tablets and functional foods make it more accessible for use in the long-term diet. But there are still some drawbacks, such as poor large-scale clinical validation, limited shelf life and not being dosage standardized. In general, wheatgrass is a promising way to support a complementary nutritional approach to diabetes prevention and management, but further studies at the molecular and clinical level are needed to prove its therapeutic effectiveness.

Keywords: Phytochemicals, Standardization, Wheatgrass, Nutraceuticals

INTRODUCTION

Herbal medicines are considered the major healthcare provider in the whole world, mainly in rural and remote areas. Herbal plants have been used for medicinal applications for thousands of years for treating many diseases and disorders (Kozan, 2007). Nearly half of the synthetic medicines have been found to be derived from plants and around sixty-four percent of the entire human population is known to make good use of the plant-based medicine for treating various ailments. In the Indian medical system fifteen hundred medicinal herbs have been mentioned and five hundred species of these herbs are used extensively in the preparation of medicines (Ali, 2012). Herbs are meant to be in harmony with nature and, therefore, safe. The concept of nutraceuticals has become a novel way to fill the gap between nutrition and healthcare, especially in the fields of chronic disease prevention and management. Nutraceuticals are food derived products with health benefits, beyond their basic nutritional function, that may have therapeutic and protective effects in various diseases. The scientific interest in plant-based nutraceuticals has been growing in recent years because of the ease of employing them, their cost-effective and low side effect benefits compared to traditional medicines.

Diabetes mellitus (DM) is an endocrinological metabolic disorder that manifests with hyperglycaemia due to an impaired insulin secretion, insulin action or both, and which affects the metabolism of carbohydrates, protein and fat. The IDF Diabetes Atlas 2021 estimates that 537 million adults (aged 20-79) were living with diabetes in 2021. It significantly impacts on the health condition, quality of life and longevity of patients and health care system (Sun et al. 2021). Most new treatments for type 2 diabetes mellitus are drugs that either stimulate insulin production or reduce blood glucose. Some people have been known to develop insulin resistance as a result of a sedentary lifestyle, obesity, and fast meals. The insulin resistance of muscle and fat cells reduces the amount of glucose they take up, and the insulin resistance of the liver cells reduces the amount of glycogen they store and the ability to control their release of glucose into blood. Naturopathy is a branch of medicine that aims to maintain optimum health in a person through several natural therapeutic practices, such as lifestyle management, herbal medicine and nutrition management (wigmore, 1985).

The plants play a vital role in the life of the planet too, they are needed for food and fodder, shelter, medicines and for economic purposes etc. The significance of medicinal plants in regards to human health and wellness is recognized. Since ancient times, medicinal plants are the sources of medicines (medicines) and have been used by humans as the main medicines (Medicines) sources (Pan et al., 2014). The term "wheatgrass" describes the young grass of the common wheat plant (Triticum aestivum), which is used to make powder or freshly juiced food for both humans and animals. Wheatgrass is what is known as wheat that germinates in 6-10 days. Wheatgrass juice is the most powerful medicine known in nature, also containing antioxidant properties. It has a beneficial effect on health and is more effective than synthetic vitamins and supplements. The juices of wheatgrass are full of chlorophyll, an ingredient that helps detoxify and purify the body. Is an automatic detoxifier (Edward et al., 1999). Harmful effects of free radicals are eliminated by the action of and bioactive chemicals. Wheatgrass juice has been found to exhibit antioxidant, bioactive and immunomodulatory properties (Khushi et al., 1999) which may influence blood sugar levels by increasing the insulin receptor sensitivity. Starvation during gestation (Coulston et al., 2008) may make individuals more resistant to insulin and diabetes with an increase in weight.

Bioactive components of wheatgrass

Vitamin A: It provides a healthy look to the skin's outer layer, prevents illness and provides a brighter shine to the skin. It enhances eye vision by getting rid of dark circles around the eyes and black spots on the skin. Not only does it nourish hair, it is also effective in combating pollution. Vitamin A is required for good vision, proliferation and normal growth and development. Furthermore, it protects against eye, nose and throat ailments.

Vitamin B: It helps to absorb. It can be utilized for anorexia, sadness, wretchedness, rest issues, stomach issues and early maturing.

Vitamin C: Vitamin C is an excellent cell bolstering that is useful for working on immune reactions and aiding in recuperation from a range of conditions, including cold virus. It's a vital part of a healthy mouth, gums and bones. It is a vital need in the body, a necessity and a cure for wounds and injuries. It is a typical hotspot for compounds that are anti-toxic. Wheatgrass contains good amount of vitamin C.

Vitamin E: Is an effective treatment for dysmenorrhea, diabetes, cancer, impotence and other conditions. A deficiency of this fat-soluble vitamin results in sterility, muscle atrophy and delayed recovery from diseases and injuries. Vitamin E is a substance which strengthens, enriches the cells and also protects the heart.

Vitamin K and B complex Vitamins: Vitamin B-17 or Amygdaline can be found in wheatgrass and can help prevent the carcinogenic growth. Wheatgrass has 17 Amino Acids and 92 minerals which are essential for the human body. It is also said that the vitamins in wheatgrass aid in the prevention of disease and repair of lung cell damage.

Protein and Amino Acids: Proteins are key for style and powerful muscles. Chemicals, antibodies and plasma are extracted from proteins. Amino acids help to build blood, promote processing and provide the heart with vitality.

Wheat grass Juice: Enzymes in wheat grass juice can aid in the treatment of dyspepsia. They are beneficial in absorption, help build a strong physique, and counteract premature aging.

Polyphenols: Polyphenols are a broad group of secondary metabolites which have shown to have strong antioxidant activity. The polyphenolic compounds present in wheatgrass play a crucial role in the elimination of reactive oxygen species (ROS) and reduction of oxidative stress. They also can help to prevent chronic diseases such as diabetes by modifying the way cells communicate and improving the way they work. (Kulkarni et al., 2006).

Flavonoids: Wheatgrass is rich in flavonoids, which are an important class of polyphenol. A variety of flavonoids, such as luteolin, apigenin and quercetin, are known for their potent antioxidant and anti-inflammatory properties. These are associated with enhanced insulin sensitivity, blockage of carbohydrate-digesting enzymes, and decrease in inflammation, which are all important for glycaemic management and metabolic regulation (Singh et al. 2012).

Phenolic compounds: Ferulic acid, caffeic acid and vanillic acid are all phenolic acids present in wheatgrass. These chemicals are superior free radical scavengers and play a part in decreasing oxidative damage to the cells. They have a strong effect on enhancing the total antioxidants in wheatgrass and its role in controlling diabetes complications (Padalia et al., 2010).

Chlorophyll: Wheatgrass contains a significant amount of chlorophyll, which makes up a large proportion of the total pigments found in wheatgrass. It is a cleansing, antioxidant and anti-inflammatory agent. The chlorophyll is similar in structure to haemoglobin, and is believed to assist in the transport of oxygen and in the quality of blood. In diabetes, chlorophyll decreases oxidative stress, is anti-oxidative and prevents damage to pancreatic β-cells (Rana et al., 2011).

Bioactive Compound	Class	Key Components	Biological Functions	References
Chlorophyll	Pigment	Chlorophyll a, b	Detoxification, antioxidant activity, supports hemoglobin synthesis	Rana et al., 2011
Flavonoids	Polyphenols	Quercetin, Apigenin	Anti-inflammatory, antioxidant, improves insulin sensitivity	Singh et al., 2012; Padalia et al., 2010
Phenolic Acids	Polyphenols	Ferulic acid, Caffeic acid	Free radical scavenging, reduces oxidative stress	Kulkarni et al., 2006
Vitamins	Micronutrients	A, C, E, B-complex	Antioxidant defense, metabolic regulation	Chauhan, 2014
Minerals	Micronutrients	Magnesium, Zinc, Iron	Enzyme activation, glucose metabolism	Singh et al., 2012
Enzymes	Biological catalysts	SOD, Catalase	Neutralize ROS, protect cells	Kulkarni et al., 2006
Dietary Fiber	Carbohydrate	Soluble/insoluble fiber	Slows glucose absorption	Rana et al., 2011

Role of Wheatgrass in Diabetes Management

The anti-diabetic and therapeutic properties of wheatgrass (Triticum aestivum) have been of great interest as a functional diet and nutraceutical. The therapeutic value of its extracts is mainly due to its rich content of bioactive ingredients, including chlorophyll, flavonoids, phenolic acids, vitamins, minerals, and antioxidant enzymes. Wheatgrass (Triticum aestivum) has recently become a functional food and nutraceutical with emphasis on its role in the prevention and management of diabetes mellitus. The therapeutic properties are due to its wide array of bioactive ingredients such as chlorophyll, flavonoids, phenolic acids, vitamins, minerals and antioxidant enzymes.

Glycemic Control: Wheatgrass has been reported to have a hypoglycemic effect, which is the ability to moderate one's blood glucose levels. It stimulates insulin release and increases glucose uptake in the periphery, thus helping to control glycemia. Moreover, wheatgrass has been shown to inhibit the enzymes responsible for the digestion of carbohydrates including α-amylase and α-glucosidase, thereby helping to prevent postprandial hyperglycemia (Padalia et al., 2010; Singh et al., 2012).

Antioxidant Activity: Oxidative stress is at the heart of the pathogenesis of diabetes and its complications. Wheatgrass is packed with antioxidants like flavonoids, phenolic compounds, vitamins C and E, which are effective in scavenging reactive oxygen species (ROS). Antioxidant activity protects pancreatic β-cell from oxidative damage and enhances metabolic activity as well (Kulkarni et al., 2006; Chauhan, 2014).

Enhance Insulin Signaling Pathways and Decrease Insulin Resistance: Flavonoids such as quercetin and apigenin, found in wheatgrass, increase insulin signaling pathways and diminish insulin resistance. Increased insulin sensitivity will help the tissues to use glucose efficiently and will help reduce blood glucose levels (Singh et al., 2012).

Anti-inflammatory Effects: One of the hallmarks of type 2 diabetes is chronic low-grade inflammation. Wheatgrass has anti-inflammatory effects, blocking pro-inflammatory cytokines and mediators. This decrease in inflammation results in better insulin action and metabolic homeostasis (Rana et al., 2011).

Diabetes is often accompanied by dyslipidemia, which includes high triglycerides and low-density lipoprotein (LDL) cholesterol. Wheatgrass supplementation has been demonstrated to lower LDL and triglyceride levels, thus minimizing cardiovascular problems (Chauhan, 2014).

Detoxification and Cellular Protection: Wheatgrass's chlorophyll is a significant element that will serve in detoxification and cellular repair. It improves oxygen transport and promotes tissue regeneration that can play a role in reducing complications of chronic hyperglycemia (Rana et al., 2011).

Role as a Nutraceutical

Wheatgrass is a nutraceutical, and therefore a natural and inexpensive way to manage diabetes for long-term. The fruit can be consumed in the form of fresh fruit juice, powder and supplement and is available and appropriate for dietary intervention (Padalia et al., 2010).

Form	Description	Health Benefits	References
Fresh Juice	Extract of young leaves	Improves antioxidant status, quick absorption	Chauhan, 2014
Powder	Dehydrated wheatgrass	Convenient, supports daily intake	Rana et al., 2011
Tablets/Capsules	Concentrated extract	Controlled dosage	Singh et al., 2012
Functional Foods	Fortified foods	Enhances compliance	Padalia et al., 2010
Extracts	Standardized bioactives	Targeted therapeutic effects	Kulkarni et al., 2006

Wheatgrass (Triticum aestivum) is a plant that has great potential as a functional food and nutraceutical, but has certain limitations that pose an obstacle to its widespread use in human therapy. One of the limitations of wheatgrass is that there are a lack of well-designed, long-term human clinical trials. Most of the existing information is from in vitro studies, animal models or small-scale pilot trials. According to a large review, wheatgrass has been shown to treat many illnesses such as diabetes, obesity, oxidative stress and inflammatory conditions, but most of the clinical studies were limited and lacked methodological rigor. Wheatgrass can be taken as fresh juice, frozen juice, granules, tablets or capsules. However, the concentration of bioactive compounds can vary greatly depending on the growth stage, cultivation conditions, and harvesting time and method. This heterogeneity results in inconsistent effects and standardized dosing is difficult (Bar-sela et al, 2015). Fresh wheatgrass juice is extremely perishable, meaning that after extraction chlorophyll, vitamin C, enzymes and other sensitive phytochemicals are rapidly destroyed. Though drying and powdering increase the shelf life, it may also reduce some mineral content as well as antioxidant activity that are sensitive to heat (Bangera et al, 2025). Those who are genetically susceptible, especially those with wheat sensitivity or grass allergies, may experience allergic or hypersensitive reactions to wheatgrass. Wheatgrass is susceptible to bacterial, fungal and mold infection due to its high raw consumption as fresh juice. Children and elderly individuals, pregnant women and those with weakened immune systems are at the highest risk of this threat (Gunjal et al, 2024).

Conclusion

The wheatgrass Triticum aestivum has proven to have a high potential as a nutraceutical with bioactive properties in the prevention and management of diabetes mellitus. The therapeutic effects have been attributed to the synergism of its active ingredients, such as chlorophyll, polyphenols, flavonoids, phenolic compounds, vitamins, minerals and antioxidant enzymes, which contribute to better glycemic control, higher insulin sensitivity, decrease in oxidative stress, and modulation of inflammatory response. The different forms of wheatgrass like fresh juice, powder, tablets and fortified functional foods further reinforces its suitability for a sustainable dietary intervention. However, issues like limited clinical trials in humans, inconsistencies in phytochemical composition, dosage and storage complications are still a challenge to the translation into clinical use. Thus, wheatgrass may be viewed at this time as a nutraceutical supplement to diabetes treatment instead of replacement for it. To establish its role in precision nutrition and integrative diabetes management, further validation through standardized formulations, understanding of molecular mechanisms, and larger randomized clinical trials will be crucial.

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Genetic Susceptibility and Modifiable Determinants of Type 2 Diabetes Mellitus: Environmental and Lifestyle Contributions

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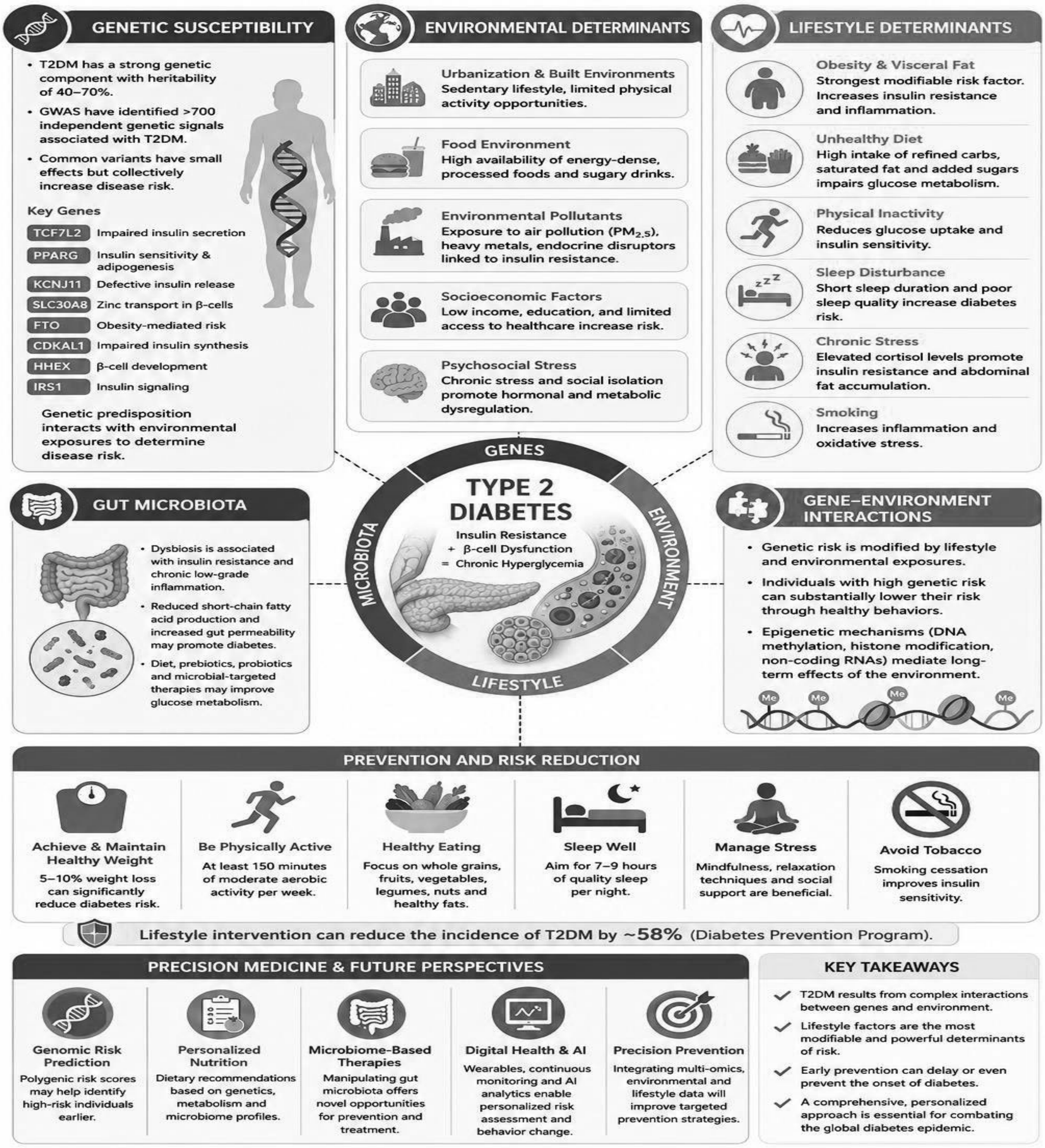
Key Points

- Type 2 diabetes mellitus (T2DM) is a multifactorial metabolic disorder resulting from interactions between inherited genetic susceptibility and environmental exposures.
- Genetic variants influence insulin secretion, insulin sensitivity, adiposity, and glucose homeostasis.
- Obesity remains the strongest modifiable risk factor for T2DM worldwide.
- Dietary patterns, physical activity, sleep quality, psychosocial stress, and environmental pollutants significantly influence disease risk.
- Gene–environment interactions determine whether inherited susceptibility progresses to overt diabetes.
- Socioeconomic status, urbanization, dietary transitions, and early-life developmental exposures play critical roles in shaping metabolic health and contribute significantly to the global rise of T2DM.
- Gut microbiota have emerged as important modulators of glucose metabolism and insulin sensitivity.

- Precision medicine approaches integrating genomics and lifestyle factors may improve future prevention strategies.

Summary

Type 2 diabetes mellitus (T2DM) has become one of the most important health challenges in the twenty-first century worldwide. The disease is most commonly linked to obesity, poor dietary practices and lack of physical activity. However, a large body of research has demonstrated that genetic predisposition is also an important determinant of individual risk. Hence, the development of T2DM can be best described as a result of continual interactions between inherited genetic factors and modifiable environmental exposures. The current chapter describes the main genetic variants associated with susceptibility to diabetes and the role of environmental determinants such as urbanization, pollution, socioeconomic status and lifestyle behaviors in the development of the disease. Obesity, dietary patterns, physical inactivity, sleep disturbances and psychosocial stress are highlighted as important modifiable risk factors. This chapter also emphasizes the emerging role of gut microbiota in glucose metabolism and insulin sensitivity. Recent evidence indicates that beneficial lifestyle interventions can substantially lower diabetes risk even in people with high-risk genetic variants. In addition, developments in genomics, epigenetics, artificial intelligence and precision medicine are opening up new avenues for personalized prevention and early intervention strategies. Understanding gene-environment interaction is crucial to reduce the global burden of T2DM, and to develop effective public health policies aimed at disease prevention and the promotion of metabolic health.



Graphical Highlights

- Genetic predisposition influences diabetes susceptibility but does not guarantee disease development.
- Obesity remains the strongest modifiable risk factor for T2DM.
- Diet, physical activity, sleep quality, and stress management significantly affect disease risk.

- Environmental pollutants and socioeconomic factors contribute to metabolic dysfunction.
- Gut microbiota play an emerging role in glucose homeostasis and insulin sensitivity.
- Healthy lifestyles can offset a substantial proportion of inherited genetic risk.
- Precision medicine approaches may improve future diabetes prevention and management

1. Introduction

The chronic metabolic disease known as type 2 diabetes mellitus (T2DM) is typified by persistent hyperglycemia brought on by either increasing pancreatic β-cell failure, decreased insulin action, or a combination of the two. About 90–95% of all occurrences of diabetes are type 2 diabetes (T2DM), which has emerged as one of the world's most urgent health issues. Due to its consequences, which include cardiovascular disease, nephropathy, neuropathy, and retinopathy, the rising incidence of type 2 diabetes is linked to significant morbidity, death, and healthcare costs.Over 500 million persons worldwide have diabetes, according to latest estimates from the International Diabetes Federation, and this figure is predicted to rise dramatically over the next several decades. Genetic factors alone cannot account for the significant rise in diabetes prevalence. Rather, the onset of disease has been significantly influenced by changes in environmental exposures, dietary habits, levels of physical activity, and social determinants of health.In the past, diabetes was thought to only affect wealthy people. However, the burden of disease has increased in low- and middle-income nations due to urbanization, globalization, and dietary changes. The global diabetes pandemic has intensified due to the confluence of genetic predisposition and unfavorable environmental factors.According to current research, type 2 diabetes is a complex condition brought on by ongoing interactions between genetic, environmental, behavioral, and metabolic variables. Developing successful preventative techniques and individualized therapies requires an understanding of these connections.

2. Genetic Architecture of Type 2 Diabetes Mellitus

A significant part of the pathophysiology of type 2 diabetes involves genetic predisposition. People with diabetic parents are much more likely to develop diabetes than people without a family history, according to several family studies. According to twin studies, concordance rates range from around 60% to 90%, indicating a significant genetic component. The development of genome-wide association studies (GWAS) transformed our knowledge of the genetics of diabetes. More than 700 distinct genetic markers and several hundred susceptibility loci have been linked to type 2 diabetes as a result of these studies. The majority of variations have little impacts on their own, but when combined, they greatly change the risk of illness. TCF7L2, a transcription factor linked in Wnt signaling pathways and pancreatic β-cell activity, is one of the most researched susceptibility genes. In a variety of groups, variations in this gene consistently exhibit the highest correlation with type 2 diabetes. Insulin secretion and glucose control are hampered by risk alleles.PPARG is another crucial gene that controls insulin sensitivity, lipid metabolism, and adipocyte development. Additionally, thiazolidinedione medications used to treat diabetes have PPARG as their therapeutic target. The location of adipose tissue and metabolic activity are influenced by genetic variation within this gene.A potassium channel implicated in glucose-stimulated insulin release is encoded by the KCNJ11 gene. Variants that impact channel activity can worsen β-cell responsiveness and raise the risk of diabetes. In a similar vein, SLC30A8 encodes a zinc transporter necessary for the production of insulin granules and appropriate insulin secretion. Genes linked to obesity indirectly contribute to the development of diabetes.

Table 1. Major Genetic Variants Associated with Type 2 Diabetes Mellitus

Gene	Chromosome	Biological Function	Mechanism in T2DM	Clinical Significance
TCF7L2	10q25.2	Wnt signaling	Reduced insulin secretion	Strongest common susceptibility locus
PPARG	3p25	Adipocyte differentiation	Insulin resistance	Target of thiazolidinediones
KCNJ11	11p15	Potassium channel regulation	Defective insulin release	Pharmacogenetic importance
SLC30A8	8q24	Zinc transport	Altered insulin granule formation	β-cell dysfunction
FTO	16q12	Energy homeostasis	Obesity-mediated diabetes risk	Associated with BMI
IRS1	2q36	Insulin signaling	Reduced glucose uptake	Insulin resistance

HHEX	10q23	Pancreatic development	β-cell dysfunction	Early disease susceptibility
CDKAL1	6p22	Insulin biosynthesis	Impaired insulin secretion	Common risk variant
MC4R	18q21	Appetite regulation	Obesity and metabolic syndrome	Weight regulation
KLF14	7q32	Adipose tissue regulation	Altered lipid metabolism	Parent-of-origin effects

The FTO gene influences appetite regulation, body weight, and adiposity. Current evidence suggests that the diabetogenic effect of FTO is largely mediated through obesity rather than direct alterations in glucose metabolism. The recognition of multiple susceptibility loci has led to the development of polygenic risk scores (PRS). These scores combine information from numerous genetic variants to estimate inherited disease risk. Although promising, their clinical implementation remains limited because predictive performance varies among ethnic populations.

3. Environmental Determinants of Type 2 Diabetes Mellitus

Diabetes risk is significantly influenced by environmental variables. Rapid industrialization and urbanization have changed living conditions and greatly increased the prevalence of metabolic illnesses worldwide. Opportunities for physical exercise, food choices, and social behaviors are all influenced by the built environment. Sedentary lifestyles and obesity are frequently encouraged in communities that lack parks, recreational amenities, and safe places to stroll. Diabetes is more common in urban populations than in rural ones, according to several research. Food settings are just as significant. Excessive calorie consumption and metabolic dysfunction are caused by an increase in the availability of energy-dense processed meals high in refined carbs, saturated fats, and added sugars. On the other hand, having access to whole grains, fresh produce, and nutritious dietary alternatives is linked to a decreased incidence of diabetes. It has become clear that environmental contaminants have a significant role in metabolic diseases. Insulin resistance and poor glucose metabolism have been linked to long-term exposure to airborne particulate matter (PM2.5), persistent organic pollutants, endocrine-disrupting chemicals, arsenic, cadmium, and other toxicants. These compounds have the potential to cause β-cell destruction, oxidative stress, inflammation, and mitochondrial dysfunction. Another significant factor influencing the risk of illness is socioeconomic status. Lifestyle choices and exposure to environmental dangers are influenced by factors such as employment circumstances, healthcare access, financial level, and educational achievement. Healthy living circumstances and preventative healthcare are sometimes more difficult to get for those from socioeconomically disadvantaged families. Psychosocial stress associated with financial insecurity, occupational pressures, and social inequalities may further contribute to metabolic dysfunction through chronic activation of stress-response pathways.

4. Lifestyle Determinants of Type 2 Diabetes Mellitus

Lifestyle behaviors are the most important modifiable determinants for the development of T2DM. Obesity is the best predictor of T2DM. Excess adipose tissue, especially visceral fat accumulation, predisposes to insulin resistance through increased release of free fatty acids, pro-inflammatory cytokines and adipokines. Obesity related low grade inflammation additionally impairs insulin signaling pathways. Diet is a major determinant of metabolic health. Eating lots of sugar-sweetened drinks, refined grains, processed meats and ultra-processed foods increases the risk of diabetes. They can result in postprandial hyperglycaemia, oxidative stress and insulin resistance. Conversely, diets high in whole grains, legumes, fruits, vegetables, nuts and unsaturated fats enhance insulin sensitivity and glycemic control. Physical activity is crucial for maintenance of glucose homeostasis. Exercise increases glucose uptake in skeletal muscle , improves mitochondrial function , improves insulin sensitivity , and promotes healthy body weight. Regular moderate-to-vigorous physical activity is associated with a significantly reduced risk for diabetes.

Table 2. Major Modifiable Determinants and Their Biological Effects on Type 2 Diabetes Development

Determinant	**Primary Biological Mechanism**	**Impact on Diabetes Risk**	**Modifiable**
Obesity	Insulin resistance and inflammation	Very High	Yes
Visceral adiposity	Increased free fatty acids	Very High	Yes
Physical inactivity	Reduced glucose uptake	High	Yes

Unhealthy diet	β-cell stress and obesity	High	Yes
Sugar-sweetened beverages	Hyperglycemia and weight gain	High	Yes
Sleep deprivation	Hormonal dysregulation	Moderate	Yes
Chronic stress	Elevated cortisol	Moderate	Yes
Smoking	Oxidative stress	Moderate	Yes
Air pollution	Systemic inflammation	Moderate	Partially
Heavy metal exposure	Metabolic disruption	Moderate	Partially
Shift work	Circadian disruption	Moderate	Partially
Low socioeconomic status	Reduced healthcare access	Moderate	Indirectly

Sedentary behaviour is an independent contributor to metabolic dysfunction. Sitting for long periods of time reduces energy expenditure and impairs glucose utilization, even in people who otherwise meet the exercise recommendations. Sleep quality has become an important determinant of metabolic health. Short sleep duration, circadian disruption and poor sleep quality are associated with greater insulin resistance and diabetes risk. These effects are linked to hormonal changes such as cortisol, leptin, ghrelin and melatonin. Chronic psychological stress is also a contributor to disease development. Activation of the hypothalamic pituitary–adrenal axis leads to increased production of cortisol, insulin resistance and obesity.

5. Gut Microbiota and Type 2 Diabetes Mellitus

The trillions of bacteria that make up the gut microbiota are found in the human gastrointestinal system. A growing body of research indicates that these microbial communities are crucial for controlling immunological responses, energy homeostasis, insulin sensitivity, and glucose metabolism. Dysbiosis, or changes in the composition of gut microbes, is often seen in people with type 2 diabetes. These changes may enhance intestinal permeability, promote chronic low-grade inflammation, and decrease the generation of advantageous short-chain fatty acids. These alterations may lead to metabolic dysregulation and impede insulin signaling. Through a variety of processes, such as the control of bile acid metabolism, the modification of inflammatory pathways, the generation of microbial metabolites, and interactions with the immune system, gut microbiota affect host metabolism. Microbial composition is significantly influenced by dietary variables, suggesting a possible connection between nutrition and diabetes risk. Probiotics, prebiotics, microbiota-targeted treatments, and dietary changes may all enhance metabolic outcomes, according to recent study. These methods show promise for future diabetes prevention and treatment, even if they are still being researched.

6. Gene–Environment Interactions in Type 2 Diabetes Mellitus

Gene-environment interactions are a central concept in the pathogenesis of diabetes. Genetic susceptibility alone is not enough to explain disease development but rather inherited risk factors function in a continuous interaction with environmental exposures and lifestyle behaviors across the life span. Individuals with high-risk variants in genes like TCF7L2 may be more sensitive to unhealthy dietary patterns and obesity. In the same vein, genes associated with obesity are often more influential when there is excess calorie intake and insufficient exercise. Large cohort studies show that even among individuals with high genetic susceptibility, healthy lifestyles substantially reduce disease risk. The Diabetes Prevention Program found that among high-risk adults, an intensive lifestyle intervention reduced the incidence of diabetes by almost 58%. Numerous gene-environment interactions can be biologically explained by epigenetic processes. Environmental exposures can change non-coding RNA expression, histone modifications, and DNA methylation, which can affect gene function without altering DNA sequence. Long-term metabolic programming and disease vulnerability may be influenced by these modifications. Determining high-risk individuals and creating focused preventative measures require an understanding of gene-environment interactions.

7. Precision Medicine and Future Perspectives

Precision medicine seeks to combine genetic, clinical, environmental, and behavioral data to improve the prevention and treatment of disease. Polygenic risk scores may be useful to identify individuals at increased risk prior to disease onset. However, challenges regarding population diversity, predictive accuracy and clinical implementation need to be overcome before widespread adoption. Another promising approach is personalized nutrition. The individual response to dietary interventions is highly variable, owing to differences in genetics, metabolism and gut microbiota composition. Precision nutrition aims to tailor dietary recommendations to these factors. Artificial intelligence and machine-learning technologies are increasingly used to integrate complex datasets and enhance disease prediction. Digital health tools, wearable devices and continuous glucose monitoring systems further support personalized care opportunities. Future integration of genomics, epigenomics, metabolomics, microbiome and environmental health will shed light on the pathogenesis of T2DM and guide personalized prevention.

Conclusion

Type 2 diabetes mellitus (T2DM) is a complex multifactorial disorder due to interactions of genetic susceptibility, environmental exposures, lifestyle behaviors, and metabolic factors. Genomic research has advanced and identified multiple susceptibility genes that are involved in insulin secretion, insulin sensitivity and energy metabolism. But the contemporary diabetes epidemic is primarily driven by environmental and lifestyle factors. Obesity, unhealthy dietary habits, physical inactivity, sleep disturbances, psychosocial stress and environmental pollutants are important contributors to disease development. New evidence also points to a role for gut microbiota in metabolic regulation and the pathogenesis of diabetes. Importantly, even genetically predisposed individuals can dramatically reduce the risk of diabetes through beneficial lifestyle changes. Future prevention strategies that incorporate genomics, precision nutrition, microbiome science, and digital health technologies present encouraging prospects for lowering the global burden of type 2 diabetes.

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Impact of Structured Sports Training on Metabolic Health in Individuals with Diabetes

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Abstract

Diabetes mellitus is a chronic metabolic disorder characterized by persistent hyperglycemia resulting from defects in insulin secretion, insulin action, or both. The global prevalence of diabetes has increased significantly due to sedentary lifestyle, obesity, and unhealthy dietary habits. Structured sports training has emerged as an effective non-pharmacological intervention for improving metabolic health among individuals with diabetes. Structured sports training refers to planned, supervised, and progressive physical activity programs that include aerobic exercise, resistance training, flexibility, and sport-specific movements. These interventions improve insulin sensitivity, enhance glucose uptake by skeletal muscles, reduce body fat percentage, and improve cardiovascular fitness. Evidence from clinical studies suggests that regular participation in structured sports programs can reduce glycated hemoglobin (HbA1c), improve lipid profile, regulate blood pressure, and enhance overall metabolic control in both type 1 and type 2 diabetes patients. Additionally, sports training improves psychological well-being, reduces stress, and enhances quality of life. This chapter discusses the clinical perspective of diabetes, including diagnostic criteria, pathophysiology, and pharmacological management, and highlights the role of structured sports training in improving metabolic health and long-term disease management. Diabetes mellitus is one of the most prevalent metabolic disorders affecting millions of people worldwide.It is characterized by chronic hyperglycemia resulting from defects in insulin secretion, insulin action, or both. The management of diabetes involves a combination of pharmacological therapy, lifestyle modification, nutritional management, and regular physical activity. Among lifestyle interventions, exercise has been recognized as a powerful strategy for improving metabolic health and preventing diabetes-related complications. Structured sports

training represents a dynamic and engaging approach to physical activity. Unlike traditional exercise programs, sports training incorporates systematic planning, progressive overload, and sport-specific conditioning strategies. Participation in structured sports activities such as football, badminton, athletics, basketball, swimming, and other recreational sports provides both aerobic and anaerobic exercise stimuli that enhance metabolic function. Recent research in sports medicine and physiotherapy suggests that structured sports training can significantly improve glycemic control, insulin sensitivity, lipid metabolism, and body composition in individuals with diabetes. In addition to physiological benefits, sports participation promotes psychological well-being, social interaction, and long-term adherence to physical activity programs. This chapter discusses the impact of structured sports training on metabolic health in individuals with diabetes. It highlights physiological mechanisms, training principles, metabolic adaptations, safety considerations, and practical strategies for implementing sports-based exercise programs. Graphical trends are also presented to illustrate improvements in metabolic indicators such as HbA1c levels, blood glucose levels, and body fat percentage during structured training programs.

1.Introduction

This chapter propose to examine two aspects of the relationship between diabetes mellitus and exercise. Firstly, the adjustments the athelete with diabetes might make if he or she wishes to exercise and secondly , what the risks and benefits are both in the short term and long term, of exercise to the Patient with diabetes.

There are many examples of atheletes with diabetes who have been extremely successful. British rower steven redgrave developed diabetes at the age of 35 having won medals at each of the previous four Olympic games.Following his diagnosis he was able to secutive gold medal in the Sydney Olympics in 2000.

There are two distinct types of diabetes mellitus: insulin-dependent(type 1)and non- insulin dependent(type 2) diabetes mellitus is a metabolic disorder characterized by high blood glucose levels due to defects in insulin production, insulin action, or both. In the context of sports and physical activity, understanding diabetes is important because exercise significantly influences blood glucose levels, insulin sensitivity, and overall metabolic health. Athletes and physically active individuals with diabetes can safely participate in sports with proper monitoring, nutrition, and medical guidance.

This chapter propose to examine two aspects of the relationship between diabetes mellitus and exercise. Firstly, the adjustments the athelete with diabetes might make if he or she wishes to exercise and secondly , what the risks and benefits are both in the short term and long term, of exercise to the Patient with diabetes. There are many examples of atheletes with diabetes who have been extremely successful. British rower steven redgrave developed diabetes at the age of 35 having won medals at each of the previous four Olympic games.Following his diagnosis he was able to secutive gold medal in the Sydney Olympics in 2000. There are two distinct types of diabetes mellitus: insulin-dependent(type 1)and non- insulin dependent(type 2)

Type 1 diabetes : Type 1 diabetes is an autoimmune condition in which the immune system attacks and destroys insulin-producing beta cells in the pancreas. As a result, the body produces little or no insulin, and individuals must rely on insulin therapy for survival.

Causes

The exact cause of Type 1 diabetes is not fully known, but it is believed to involve genetic factors and environmental triggers such as viral infections. The immune system mistakenly attacks the pancreatic beta cells responsible for producing insulin.

Symptoms

Common symptoms include increased thirst, frequent urination, unexplained weight loss, fatigue, blurred vision, and increased hunger. These symptoms often develop rapidly.

Type 1 Diabetes in Sports

People with Type 1 diabetes can actively participate in sports, including competitive athletics. Exercise helps improve cardiovascular fitness, muscle strength, and insulin sensitivity. However, athletes must carefully monitor blood glucose levels before, during, and after exercise.

Important considerations for athletes with Type 1 diabetes include:

- Monitoring blood glucose regularly
- Adjusting insulin dosage before exercise
- Consuming appropriate carbohydrates before and during activity
- Preventing hypoglycemia (low blood sugar) during prolonged exercise
- Maintaining hydration and proper recovery after sports activity

Type 2 Diabetes : Type 2 diabetes is a metabolic disorder characterized by insulin resistance and relative insulin deficiency. In this condition, the body does not use insulin effectively, leading to elevated blood glucose levels.

Causes

Type 2 diabetes is commonly associated with lifestyle factors such as physical inactivity, obesity, unhealthy diet, and genetic predisposition. It usually develops gradually and is more common in adults, although it is increasingly seen in younger individuals.

Symptoms

Symptoms may include fatigue, increased thirst, frequent urination, slow healing of wounds, blurred vision, and recurrent infections. Sometimes the condition may remain undiagnosed for many years

Type 2 Diabetes in Sports

Physical activity plays a major role in the prevention and management of Type 2 diabetes. Regular sports participation helps improve insulin sensitivity, reduce body fat, control blood glucose levels, and enhance cardiovascular health.

Benefits of sports for individuals with Type 2 diabetes include:

- Improved glucose uptake by muscles
- Better weight management
- Reduced risk of cardiovascular disease
- Improved metabolic health
- Enhanced psychological well-being

Diabetes mellitus has emerged as a major public health challenge globally. The prevalence of both type 1 and type 2 diabetes has increased significantly over the past few decades due to sedentary lifestyles, unhealthy dietary habits, obesity, and aging populations. Chronic hyperglycemia in diabetic individuals leads to multiple long-term complications including cardiovascular disease, neuropathy, nephropathy, and retinopathy. Lifestyle interventions play an essential role in diabetes prevention and management. Among these interventions, physical activity is considered a cornerstone of metabolic control. Regular exercise improves glucose uptake by skeletal muscles, enhances insulin sensitivity, and contributes to better cardiovascular health. Traditional exercise programs such as walking, jogging, cycling, and resistance training are widely recommended for diabetic individuals. However, many individuals find these routines monotonous, leading to poor adherence. Structured sports training offers a more enjoyable and motivating alternative. Sports activities incorporate elements of competition, teamwork, and skill development, which increase motivation and participation. In recent years, sports scientists and physiotherapists have explored the role of structured sports training as an effective intervention for metabolic disorders. Structured sprots traning involves organized exercise sessions with clearly defined goals, progressive intensity, and performance monitoring.

The objective of this chapter is to examine how structured sports training influences metabolic health outcomes in individuals with diabetes and to provide evidence based recommendations for designing safe and effective sports training programs.

1. Psychopathology of Diabetes and Metabolic Dysfunction

Understanding the pathophysiology of diabetes is essential to appreciate the role of exercise interventions in its management. Diabetes mellitus results from impaired insulin secretion, insulin resistance, or a combination of both mechanisms. In type 1 diabetes, autoimmune destruction of pancreatic beta cells leads to absolute insulin deficiency. Individuals with this condition require lifelong insulin therapy to regulate blood glucose levels. Type 2 diabetes, which accounts for the majority of cases, is characterized primarily by insulin resistance. In this condition, body tissues such as skeletal muscles, liver, and adipose tissue become less responsive to insulin. As a result, glucose uptake by cells decreases, leading to elevated blood glucose levels. Chronic hyperglycemia contributes to oxidative stress, inflammation, and endothelial dysfunction.

These metabolic disturbances increase the risk of cardiovascular diseases and other c mplications. Physical inactivity further worsens insulin resistance. Lack of muscle activity reduces the expression of glucose transporter proteins (GLUT-4) in skeletal muscle cells. Consequently, glucose remains in the bloodstream instead of being utilized by muscles. Regular physical activity counteracts these metabolic disturbances. Exercise stimulates glucose uptake independent of insulin and improves insulin sensitivity during recovery. Structured sports training combines aerobic and anaerobic exercise components, producing strong metabolic adaptations that help regulate glucose metabolism.

Clinical Perspective

Diabetes mellitus is a chronic metabolic disorder characterized by persistent hyperglycemia due to defects in insulin secretion, insulin action, or both. From a clinical perspective, diabetes affects multiple organ systems including the cardiovascular system, nervous system, kidneys, eyes, and musculoskeletal system. Early identification and management are important to prevent complications.

Clinically, diabetes may present with symptoms such as polyuria (frequent urination), polydipsia (excessive thirst), polyphagia (increased hunger), unexplained weight loss, fatigue, blurred vision, and slow wound healing. In many patients with Type 2 diabetes, symptoms may develop gradually and remain unnoticed for several years.

In sports and physically active individuals, diabetes management requires careful monitoring of blood glucose levels during exercise. Exercise influences glucose metabolism and insulin sensitivity, therefore clinical assessment should include evaluation of physical activity patterns, dietary habits, medication use, and risk of hypoglycemia during sports participation.

2. Diagnosis of Diabetes

The diagnosis of diabetes mellitus is primarily based on laboratory testing of blood glucose levels. Standard diagnostic criteria are recommended by international health organizations.

Fasting Plasma Glucose (FPG)

A fasting plasma glucose test measures blood sugar after an overnight fast of at least 8 hours. A fasting glucose level of 126 mg/dL or higher on two separate occasions indicates diabetes.

Oral Glucose Tolerance Test (OGTT)

In this test, blood glucose is measured before and two hours after consuming a glucose solution. A two-hour blood glucose level of 200 mg/dL or higher indicates diabetes.

HbA1c Test

The HbA1c test measures the average blood glucose level over the previous 2–3 months. An HbA1c value of 6.5% or higher is considered diagnostic for diabetes.

Random Blood Glucose Test

A random blood glucose level of 200 mg/dL or higher in the presence of typical symptoms of diabetes is also used for diagnosis. In addition to these tests, physicians may perform additional investigations to evaluate complications such as lipid profile, kidney function tests, retinal examination, and neurological assessment.

Pharmacotherapy in Diabetes

Pharmacotherapy plays a crucial role in the management of diabetes when lifestyle modification alone is insufficient to control blood glucose levels. Treatment depends on the type of diabetes, severity of hyperglycemia, and presence of complications.

Insulin Therapy

Insulin therapy is essential for individuals with Type 1 diabetes and may also be required in advanced stages of Type 2 diabetes. Insulin helps regulate blood glucose levels by facilitating the uptake of glucose into cells.

Types of insulin include:

- Rapid-acting insulin
- Short-acting insulin
- Intermediate-acting insulin
- Long-acting insulin

Oral Antidiabetic Drugs

Oral medications are commonly used in the management of Type 2 diabetes. These drugs help lower blood glucose levels through different mechanisms.

Common classes include:

- Metformin (improves insulin sensitivity)
- Sulfonylureas (stimulate insulin secretion)
- DPP-4 inhibitors (enhance incretin hormones)
- SGLT2 inhibitors (increase glucose excretion through urine)
- Thiazolidinediones (improve insulin sensitivity in tissues)

Injectable Non-Insulin Medications

Some patients with Type 2 diabetes may require injectable medications such as GLP-1 receptor agonists. These drugs help increase insulin secretion, reduce glucagon release, slow gastric emptying, and promote weight loss.

Dietary Management of Diabetes

Dietary management plays a major role in controlling diabetes. A balanced diet helps regulate blood sugar levels, maintain body weight, and provide essential nutrients for overall health.

Goals of Dietary Management

- Maintain normal blood glucose levels
- Achieve and maintain healthy body weight
- Improve lipid profile
- Prevent diabetes-related complications
- Provide balanced nutrition

Recommended Dietary Components

- Complex Carbohydrates: Whole grains, oats, brown rice, and millets help maintain steady blood glucose levels.
- Fiber-rich Foods: Vegetables, fruits, legumes, and whole grains improve digestion and slow glucose absorption.
- Lean Proteins: Sources such as fish, eggs, pulses, tofu, and low-fat dairy support muscle health.
- Healthy Fats: Nuts, seeds, olive oil, and avocados help maintain heart health.
- Adequate Hydration: Drinking enough water helps maintain metabolic balance.

Foods to Limit or Avoid

- Refined sugar and sugary beverages
- Highly processed foods
- Trans fats and excessive saturated fats
- Excess salt intake

- High glycemic index foods

Meal Planning Strategies

- Eat small and frequent meals
- Maintain consistent meal timing
- Monitor carbohydrate intake
- Include vegetables in every meal
- Follow individualized diet plans recommended by healthcare professionals

Exercise and Diabetes

Regular physical activity is one of the most effective non-pharmacological methods for managing diabetes. Exercise increases glucose uptake by muscles and improves insulin sensitivity.

Benefits of Exercise for Diabetes

- Improves blood glucose control
- Enhances insulin sensitivity
- Helps in weight management
- Improves cardiovascular health
- Reduces risk of complications
- Improves mental health and well-being

Types of Exercise Recommended

- Aerobic Exercise: Activities such as walking, jogging, cycling, and swimming help improve cardiovascular fitness.
- Resistance Training: Strength exercises using weights or resistance bands help increase muscle mass and glucose utilization.
- Flexibility Exercises: Stretching and yoga improve joint mobility and reduce injury risk.
- Balance Training: Helps improve coordination and prevent falls.

Exercise Guidelines for Diabetic Individuals

- Engage in at least 150 minutes of moderate-intensity exercise per week

- Start with warm-up and end with cool-down
- Monitor blood glucose before and after exercise
- Stay hydrated during physical activity
- Wear proper footwear to prevent foot injuries

Precautions During Exercise

- Avoid exercise if blood glucose levels are extremely high or low
- Carry a quick source of glucose (such as fruit juice or glucose tablets)
- Adjust medication or insulin based on medical advice
- Avoid excessive or very intense exercise without supervision

6 Concept of Structured Sports Training

Meaning of Structured Sports Training

Structured sports training refers to a planned, systematic, and supervised program of physical activity designed with specific goals, intensity levels, frequency, and duration.Unlike casual or unplanned exercise, structured training follows a scientific approach that includes warm-up, conditioning exercises, skill-based sports activities, and cool-down phases. For individuals with diabetes, this type of training helps regulate blood glucose levels and improves cardiovascular and muscular health.

Physiological Benefits for People with Diabetes

Regular participation in structured sports training leads to several physiological improvements. Physical activity increases glucose uptake by skeletal muscles, reducing blood sugar levels. It also improves insulin sensitivity, allowing the body to utilize insulin more effectively. Additionally, exercise helps reduce body fat, improve lipid profiles, enhance cardiovascular endurance, and strengthen muscles. These adaptations play an important role in preventing complications associated with diabetes such as heart disease, obesity, and hypertension.

Types of Sports Training Suitable for Diabetes

Several forms of sports and physical training are beneficial for individuals with diabetes. Aerobic activities such as brisk walking, jogging, cycling, swimming, and football help improve cardiovascular health and glucose metabolism. Resistance training using bodyweight exercises, resistance bands, or light weights helps increase muscle mass and improve metabolic efficiency. Flexibility and balance exercises such as stretching, yoga, and light mobility training help maintain joint health and prevent injuries.

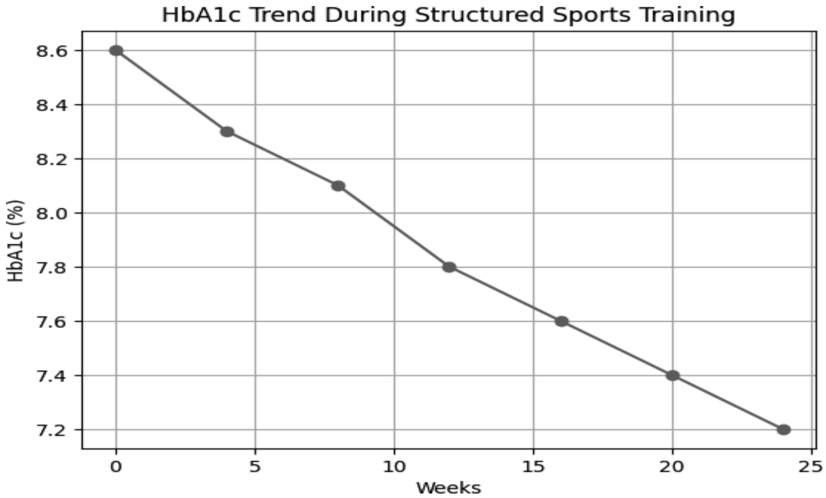
Principles of Structured Training for Diabetes

While designing a sports training program for individuals with diabetes, certain principles must be followed. The training should be gradual, starting with low intensity and progressing slowly. Regular monitoring of blood glucose levels before and after exercise is important. Hydration and proper nutrition must be maintained to avoid hypoglycemia. Warm-up and cool-down sessions are essential to prepare the body and reduce the risk of injuries. Training should also be individualized according to age, fitness level, and medical condition.

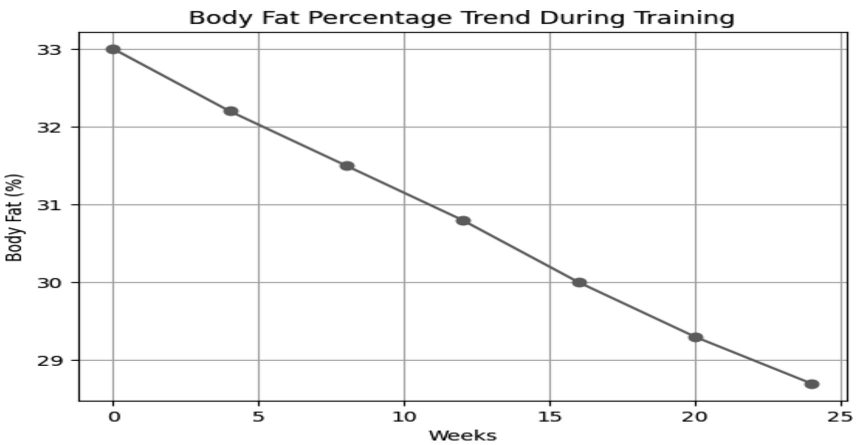
7 Graphical Representation of Metabolic Improvements

The following graphs illustrate typical trends observed in individuals who participate in structured sports training programs over a 24-week period. The first graph demonstrates the gradual reduction in HbA1c levels, which reflects improved long-term glycemic control. The second graph shows a decline in average blood glucose levels, indicating enhanced glucose utilization during physical activity. The third graph highlights reduction in body fat percentage, which contributes to improved insulin sensitivity. These graphical trends demonstrate the potential benefits of sports training as part of a comprehensive diabetes management strategy.

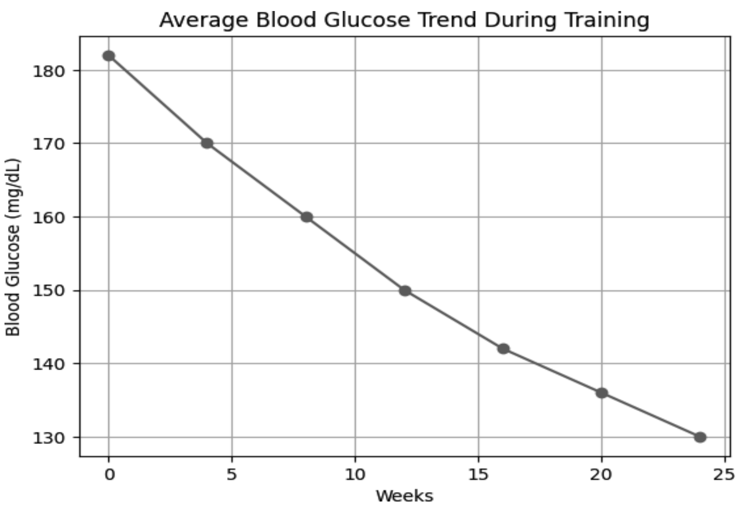
Charts



HbA1c Trend During Structured Sports Training
8.6
8.4
8.2
8.0
7.8
7.6
7.4
7.2
HbA1c (%)
0
5
10
15
20
25
Weeks



Body Fat Percentage Trend During Training
33
32
31
30
29
Body Fat (%)
0
5
10
15
20
25
Weeks



Average Blood Glucose Trend During Training
180
170
160
150
140
130
Blood Glucose (mg/dL)
0
5
10
15
20
25
Weeks

Conclusion

Structured sports training represents an effective strategy for improving metabolic health in individuals with diabetes. Through a combination of aerobic and anaerobic exercise stimuli, sports participation enhances insulin sensitivity, promotes weight management, and improves cardiovascular fitness. Incorporating sports-based physical activity into diabetes management programs can Provide both physiological and psychological benefits. Healthcare professionals, physiotherapists, and sports trainers should collaborate to design safe and individualized training programs that meet the needs of diabetic individuals. Future research should focus on long-term clinical trials examining the effectiveness of specific sports interventions in improving metabolic outcomes. The integration of sports science and clinical medicine will play a crucial role in developing innovative approaches for diabetes prevention and management.

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Gut Microbiota And Glycemic Control

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1.Introduction

Gut Microbiota

The gut microbiota refers to the vast and complex community of microorganisms, including bacteria, viruses, fungi, and protozoa, that inhabit the human digestive tract, particularly the intestines. This internal ecosystem begins its development at birth and undergoes continuous transformation throughout an individual's life, influenced significantly by diet, lifestyle, environmental factors, and the use of antibiotics. Containing trillions of microorganisms—a population that exceeds the total number of human cells in the body—these microbes are primarily beneficial, breaking down complex carbohydrates, fiber, and other food components that the human body cannot digest independently. Beyond digestion, the microbiota serves as a biological factory, synthesizing essential vitamins such as Vitamin K and the B-complex group, while simultaneously fortifying the intestinal barrier to prevent the overgrowth of harmful pathogens. Furthermore, these microbes play a foundational role in the immune system by training it to recognize threats and prevent infections; however, when this delicate balance is disrupted, a state known as dysbiosis occurs, which is linked to conditions such as Irritable Bowel Syndrome (IBS), Inflammatory Bowel Disease (IBD), and Type 2 Diabetes. Recent scientific inquiries have even expanded this influence to mental health, suggesting that the gut-brain axis connects microbial health to conditions like depression and anxiety. Ultimately, a healthy gut microbiota is a cornerstone of systemic well-being, supporting efficient metabolism, nutrient absorption, body weight regulation, and the production of life-sustaining short-chain fatty acids that reduce systemic inflammation.

2.Types of Gut Microbiota

(1)Beneficial Bacteria (Good Bacteria)

(2)Harmful Bacteria (Bad Bacteria)

(3)Opportunistic Bacteria

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Probiotics

Probiotics are live microorganisms that provide beneficial effects on health when consumed in appropriate amounts. These beneficial microbes help maintain the natural balance of gut microbiota and prevent the growth of harmful bacteria in the digestive tract. Probiotics mainly include useful bacteria and certain types of yeast that support digestive health and overall body functions. Common probiotic organisms include *Lactobacillus*, *Bifidobacterium*, *Saccharomyces boulardii*, and *Streptococcus thermophilus*. These microorganisms are naturally present in the human intestine and play an essential role in maintaining gut microbial balance.

Probiotics are commonly obtained from fermented foods such as yogurt, curd, buttermilk, kefir, cheese, and traditional fermented foods like idli and dosa. Regular intake of these foods helps increase the number of beneficial bacteria in the gut. Probiotics support digestion, improve nutrient absorption, and help manage digestive problems such as bloating, constipation, and diarrhea. They also contribute to strengthening the immune system, reducing inflammation, and supporting overall metabolic health. Additionally, probiotics help in glycemic control by improving insulin sensitivity and regulating blood sugar levels. Therefore, probiotics play an important role in maintaining gut health and overall well-being.

Prebiotics

Prebiotics are non-digestible dietary components that promote the growth and activity of beneficial bacteria in the gut. Unlike probiotics, prebiotics are not living microorganisms; instead, they serve as nourishment for the beneficial bacteria already present in the digestive system. These substances pass through the upper digestive tract without being digested and reach the large intestine, where they stimulate the growth of helpful microorganisms.

Common types of prebiotics include inulin, fructooligosaccharides (FOS), galactooligosaccharides (GOS), resistant starch, and pectin. These prebiotics are naturally found in foods such as bananas, garlic, onions, oats, barley, apples, whole grains, and legumes. Including these foods in the diet helps support beneficial gut bacteria and maintain a healthy gut microbiota.

Prebiotics improve digestive health by encouraging the growth of beneficial microorganisms, enhancing nutrient absorption, and supporting regular bowel movements. They also help reduce inflammation, strengthen immune function, and support metabolic processes. Furthermore, prebiotics contribute to glycemic control by improving glucose metabolism and reducing fluctuations in blood sugar levels. Therefore, regular consumption of prebiotic-rich foods is important for maintaining healthy gut microbiota and promoting overall health.

3.Microbial Glycemic Control and Metabolic Homeostasis

The gut microbiota plays a fundamental role in regulating blood glucose levels and maintaining normal carbohydrate metabolism by influencing how the body digests carbohydrates, absorbs glucose, produces hormones, and responds to insulin. A healthy and balanced gut microbiota is essential for maintaining stable blood sugar levels, whereas an imbalance in gut bacteria, known as **dysbiosis**, may lead to poor glycemic control and a range of metabolic disorders. This regulation occurs primarily through the microbiota's critical role in carbohydrate metabolism; when food rich in carbohydrates and fiber enters the intestine, beneficial gut bacteria break down these complex components into **short-chain fatty acids (SCFAs)** such as acetate, propionate, and butyrate. These SCFAs serve as vital signaling molecules that help improve insulin sensitivity, reduce systemic inflammation, and regulate glucose metabolism while simultaneously stimulating intestinal cells to release key hormones such as **Glucagon-like peptide-1 (GLP-1)** and peptide YY, which slow down glucose absorption and maintain normal blood sugar levels.

Beyond fermentation, the gut microbiota significantly impacts insulin resistance, which is one of the major causes of Type 2 Diabetes; when harmful bacteria increase in the gut, they produce inflammatory substances that damage the intestinal lining and allow toxins to enter the bloodstream, leading to chronic inflammation and reduced insulin sensitivity. As a result, glucose cannot enter cells properly, leading to increased blood sugar levels and a close link between microbial imbalance, diabetes, and obesity. Another important mechanism through which the gut microbiota controls glycemic levels is the regulation of bile acids and metabolism, as gut bacteria modify bile acids that influence glucose disposal and insulin secretion to help regulate energy balance. Diet plays the most significant role in this process, where high-fiber foods such as fruits, vegetables, legumes, and whole grains promote the growth of beneficial bacteria to improve glucose tolerance, while diets high in processed foods, sugar, and saturated fats increase harmful bacteria and worsen glycemic control. Incorporating fermented foods like yogurt, curd, and buttermilk further helps maintain a healthy microbiota composition, which is essential for preventing metabolic syndrome and obesity. Ultimately, poor gut microbiota composition is a major risk factor for developing insulin resistance, making the maintenance of a diverse microbial ecosystem a primary strategy for preventing metabolic diseases and achieving long-term glycemic control.

4.Functions of Gut Microbiota and Their Role in Human Health

Gut microbiota performs several important functions that are essential for maintaining human health. These microorganisms live mainly in the intestine and play a major role in digestion, metabolism, immunity, and protection against diseases. A healthy gut microbiota helps maintain normal physiological functions and supports overall body health. One of the primary functions of gut microbiota is digestion and metabolism of nutrients. The human body cannot digest certain complex carbohydrates, dietary fibers, and resistant starch on its own. Gut bacteria break down these substances and convert them into short-chain fatty acids such as acetate, propionate, and butyrate. These compounds provide energy to intestinal cells and help maintain intestinal health. Gut microbiota also helps in the digestion of proteins and fats, improving nutrient absorption and supporting overall metabolism. Another important function of gut microbiota is the synthesis of vitamins. Certain beneficial bacteria in the gut produce essential vitamins such as vitamin K and vitamin B complex, including biotin, folate, and vitamin B12. These vitamins play an important role in blood clotting, red blood cell formation, nervous system function, and energy metabolism. Without proper gut microbiota, vitamin production may decrease, leading to nutritional deficiencies. Gut microbiota also plays a major role in immune system regulation. A large portion of the immune system is located in the gut, and beneficial bacteria help strengthen immune defenses. They stimulate immune cells, enhance antibody production, and prevent the growth of harmful microorganisms. Gut microbiota also helps reduce inflammation and protects against infections. An imbalance in gut microbiota may lead to weakened immunity and increase the risk of diseases such as Inflammatory Bowel Disease and Irritable Bowel Syndrome. Another important function is protection against pathogenic microorganisms. Beneficial gut bacteria compete with harmful bacteria for nutrients and space in the intestine. They also produce antimicrobial substances that inhibit the growth of harmful microbes. This protective effect is known as colonization resistance. When beneficial bacteria are reduced, harmful bacteria may multiply and cause infections. Gut microbiota also plays an important role in maintaining the intestinal barrier. The intestinal lining acts as a protective wall that prevents harmful substances from entering the bloodstream. Beneficial bacteria help strengthen this barrier and maintain intestinal integrity. When gut microbiota becomes imbalanced, the intestinal barrier may become weak, leading to increased intestinal permeability, sometimes referred to as "leaky gut," which may contribute to inflammation and disease. Another major function of gut microbiota is metabolic regulation and glycemic control. Gut bacteria influence glucose metabolism, insulin sensitivity, and fat storage. A healthy gut microbiota helps regulate blood sugar levels and reduces the risk of metabolic disorders such as Type 2 Diabetes and Obesity. They also help regulate appetite hormones and energy balance. Type 2 diabetes is a chronic metabolic disorder in which the body becomes resistant to insulin or fails to produce enough insulin to maintain normal blood glucose levels. It is the most common form of diabetes, accounting for over 90% of cases worldwide, and is closely linked to lifestyle and genetic factors. In Type 2 diabetes, body tissues gradually lose sensitivity to insulin, the hormone that regulates blood sugar. The pancreas compensates by producing more insulin, but over time this mechanism fails. As insulin effectiveness declines, glucose accumulates in the bloodstream, leading to chronic hyperglycemia and potential long-term damage to organs such as the heart, kidneys, eyes, and nerves. Symptoms include excessive thirst, frequent urination, fatigue, blurred vision, and slow-healing wounds. Management focuses on controlling blood sugar and reducing cardiovascular risk through lifestyle modification—healthy diet, regular exercise, and weight control—and medications such as metformin or insulin. Gut microbiota is also involved in the gut-brain axis, which connects the gut and the brain. Gut bacteria produce neurotransmitters such as serotonin and dopamine, which influence mood, behavior, and mental health. Poor gut health has been associated with mental health conditions such as Depression and Anxiety Disorder. This shows that gut microbiota plays a role not only in digestion but also in mental well-being. In addition, gut microbiota helps in detoxification by breaking down harmful substances and drugs. It also plays a role in bile acid metabolism, hormone regulation, and inflammation control. These functions help maintain overall body balance and support long-term health.

5.Role of gut microbiota in type 2 diabetes

Typ e 2 diabetes is a chronic metabolic disorder in which the body becomes resistant to insulin or fails to produce enough insulin to maintain normal blood glucose levels. It is the most common form of diabetes, accounting for over 90% of cases worldwide, and is closely linked to lifestyle and genetic factors. Primarily caused by insulin resistance and relative insulin deficiency, common risk factors include obesity, a sedentary lifestyle, age, and family history, with a typical onset in adulthood, though it is increasingly seen in youth. According to World Health Organization estimates, the global prevalence exceeds 400 million people. In terms of mechanism and progression, body tissues gradually lose sensitivity to insulin, the hormone that regulates blood sugar; the pancreas compensates by producing more insulin, but over time this mechanism fails. As insulin effectiveness declines, glucose accumulates in the bloodstream, leading to chronic hyperglycemia and potential long-term damage to organs such as the heart, kidneys, eyes, and nerves. Common symptoms include excessive thirst, frequent urination, fatigue, blurred vision, and slow-healing wounds, though many individuals remain asymptomatic for years, allowing complications to develop silently. Diagnosis is typically made using fasting plasma glucose, oral glucose tolerance, or glycated hemoglobin (A1C) tests. Management focuses on controlling blood sugar and reducing cardiovascular risk through foundational lifestyle modifications—such as a healthy diet, regular exercise, and weight control—alongside medications like metformin, GLP-1 receptor agonists, SGLT2 inhibitors, or insulin, depending on disease severity. Long-term uncontrolled Type 2 diabetes can lead to serious complications, including cardiovascular disease, kidney failure, neuropathy, and retinopathy, making early detection and sustained glycemic control essential for improving long-term outcomes. Furthermore, gut microbiota is involved in the gut-brain axis, which connects the gut and the brain, as gut bacteria produce neurotransmitters such as serotonin and dopamine that influence mood, behavior, and mental health. Poor gut health has been associated with mental health conditions such as Depression and Anxiety Disorder, showing that gut microbiota plays a role not only in digestion but also in mental well-being. Additionally, gut microbiota helps in detoxification by breaking down harmful substances and drugs, while playing a role in bile acid metabolism, hormone regulation, and inflammation control to help maintain overall body balance and support long-term health.

The composition and balance of gut microbiota are influenced by several factors throughout life, including diet, antibiotics, age, stress, lifestyle, hygiene, and infections. These factors can either promote the growth of beneficial bacteria or lead to an imbalance known as dysbiosis, which may affect digestion, immunity, metabolism, and overall health. Diet is one of the most important factors influencing gut microbiota, as the type of food consumed directly affects the growth of different microorganisms; a diet rich in fiber, fruits, vegetables, and whole grains promotes beneficial bacteria that ferment dietary fiber into short-chain fatty acids to maintain intestinal health, whereas diets high in processed foods, sugar, and unhealthy fats promote harmful bacteria and increase the risk of metabolic disorders such as Obesity and Type 2 Diabetes. Antibiotics also significantly affect the gut by killing harmful bacteria but also destroying beneficial ones, which may result in reduced immunity and the overgrowth of microorganisms like Candida. Age plays a key role as the microbiota develops from birth—influenced by delivery mode and breastfeeding—and changes in diversity as individuals grow older, often decreasing in the elderly and leading to weaker immunity. Stress, both physical and emotional, can alter gut motility and microbial balance through stress hormones, potentially affecting the gut-brain axis and contributing to disorders like Irritable Bowel Syndrome. Lifestyle factors such as regular physical activity promote beneficial bacteria, while poor sleep, smoking, and a sedentary lifestyle can disturb this balance and increase inflammation. Hygiene and environmental exposure further affect development, where moderate exposure helps build a strong immune system, but excessive hygiene may reduce necessary microbial diversity. Finally, gastrointestinal infections caused by bacteria, viruses, or parasites can disrupt the normal microbial balance, leading to recurrent digestive problems and reduced immunity. In conclusion, gut microbiota is influenced by multiple factors including diet, antibiotics, age, stress, lifestyle, hygiene, and infections; therefore, maintaining a healthy diet, avoiding unnecessary antibiotics, managing stress, and follow

The gut microbiota is deeply involved in the **gut-brain axis**, a bidirectional communication network that connects the gastrointestinal tract and the central nervous system. Within this pathway, gut bacteria produce essential **neurotransmitters** such as serotonin and dopamine, which directly influence mood, behavior, and mental health; consequently, poor gut health has been clinically associated with mental health conditions such as **Depression and Anxiety Disorder**, proving that the microbiota plays a critical role in mental well-being far beyond simple digestion.

In addition to its neurological impact, the gut microbiota aids in **detoxification** by breaking down harmful substances and drugs, while also playing a vital role in **bile acid metabolism**, hormone regulation, and the control of systemic inflammation. These diverse functions are fundamental to maintaining overall homeostatic balance and supporting long-term physical health, highlighting the microbiome as a central pillar of human physiology.

6.Factors Affecting Gut Microbiota

- Diet
- Antibiotics
- Age
- Stress
- Lifestyle
- Hygiene
- Infections

The composition and balance of gut microbiota are influenced by several factors throughout life, which can either promote the growth of beneficial bacteria or lead to an imbalance known as **dysbiosis**, ultimately affecting digestion, immunity, metabolism, and overall health. **Diet** stands as one of the most critical influencers, where fiber-rich foods and whole grains promote the production of **short-chain fatty acids** to reduce inflammation, while processed sugars and unhealthy fats encourage the growth of harmful bacteria linked to obesity and Type 2 diabetes. **Antibiotics**, though necessary for treating infections, can significantly disrupt this balance by inadvertently destroying beneficial microbes, potentially leading to reduced immunity or fungal overgrowth like *Candida*. **Age** also plays a pivotal role, with the microbiome evolving from birth—influenced by delivery mode and breastfeeding—toward a diverse adult state that may eventually decline in the elderly. Furthermore, **stress** and **lifestyle** factors, including physical activity, sleep patterns, and smoking, directly alter gut motility and microbial diversity, while the "hygiene hypothesis" suggests that excessive sanitization may limit the microbial exposure needed for a strong immune system. Finally, **infections** caused by pathogens can cause acute or chronic shifts in the microbial landscape, underscoring that maintaining a healthy gut requires a holistic approach involving balanced nutrition, stress management, and the judicious use of medications.

7.Signs of Unhealthy Gut Microbiota

An unhealthy gut microbiota occurs when there is an imbalance between beneficial and harmful microorganisms in the digestive tract, a state known as **dysbiosis** that profoundly affects digestion, immunity, metabolism, and even mental health. When gut microbiota becomes unhealthy, the body starts showing several signs and symptoms that indicate poor gut function, with one of the most common signs being digestive problems; an imbalance in gut bacteria can interfere with normal digestion and nutrient absorption, leading individuals to experience indigestion, stomach discomfort, or irregular bowel movements because beneficial bacteria that help break down food are reduced while harmful bacteria increase and produce toxins that irritate the intestine. **Bloating** is another prevalent symptom, as harmful bacteria produce excessive gas during the fermentation of food in the intestine—especially foods rich in carbohydrates and fiber—leading to abdominal fullness, swelling, and discomfort. **Constipation** is also closely associated with unhealthy gut microbiota because beneficial bacteria help regulate intestinal movement and stool formation; when these populations are reduced, intestinal motility slows down, resulting in chronic difficulty passing stool and reduced microbial diversity. Conversely, **diarrhea** serves as a sign of imbalance when harmful bacteria irritate the intestinal lining and increase fluid secretion, potentially leading to persistent dehydration or the development of **Irritable Bowel Syndrome (IBS)** if the disturbance remains long-term. Beyond the gut, **fatigue** is often linked to poor gut health because impaired nutrient absorption leads to deficiencies in essential vitamins and minerals, while increased systemic inflammation further contributes to low energy levels and reduced physical performance. **Skin problems**, such as acne, eczema, and general irritation, are additional indications of dysbiosis, as gut imbalance leads to inflammation and toxin buildup that directly affects dermatological health and allergic reactions. Finally, **weak immunity** is one of the most critical signs of unhealthy gut microbiota, as a large portion of the immune system is located in the gut; when beneficial bacteria are depleted, the body becomes more susceptible to frequent infections, slow healing, and an increased risk of chronic inflammatory conditions such as **Inflammatory Bowel Disease (IBD)**.

Symptoms of Gut Microbiota Imbalance

Unhealthy Gut Microbiota

↓

Digestive Disturbances

↓

↓ ↓ ↓

Bloating Constipation Diarrhea

↓

Poor Nutrient Absorption

↓

Fatigue

↓

Skin Problems

↓

Weak Immunity

Glycemic control of gut microbiota to the vital role of intestinal microorganisms in maintaining normal blood glucose levels and regulating carbohydrate metabolism. The gut microbiota influences how carbohydrates are digested, how glucose is absorbed, and how the body responds to insulin; therefore, a healthy and balanced gut microbiota helps maintain stable blood sugar levels, while an imbalance in gut bacteria may lead to poor glycemic control and increase the risk of metabolic disorders. Gut microbiota plays an important role in carbohydrate digestion; when dietary fiber and complex carbohydrates reach the intestine, beneficial bacteria ferment these substances and produce short-chain fatty acids such as acetate, propionate, and butyrate.

These compounds improve insulin sensitivity, reduce inflammation, and help regulate glucose metabolism. Short-chain fatty acids also stimulate intestinal cells to release hormones such as **GLP-1** and **peptide YY**, which slow gastric emptying and reduce glucose absorption into the bloodstream, helping to maintain stable blood sugar levels. Another important mechanism is the regulation of insulin sensitivity; when beneficial bacteria are present in adequate amounts, insulin works more effectively, allowing glucose to enter cells and be used for energy. However, when harmful bacteria increase, they produce toxins that damage the intestinal lining and cause inflammation, which may lead to **insulin resistance**—a condition in which the body's cells do not respond properly to insulin. Insulin resistance is a major cause of Type 2 Diabetes and poor glycemic control. Furthermore, the gut microbiota influences **bile acid metabolism** and hormone regulation, as gut bacteria modify bile acids that play a role in glucose metabolism and energy balance, affecting hormone secretion and improving glucose tolerance. A healthy gut microbiota also regulates appetite and reduces excessive food intake, which helps maintain normal blood sugar levels and body weight.

Diet

plays a major role in glycemic control through gut microbiota; high-fiber foods such as fruits, vegetables, legumes, and whole grains promote the growth of beneficial bacteria and improve glucose metabolism, while fermented foods such as yogurt and curd help maintain gut microbial balance. On the other hand, diets high in sugar, processed foods, and saturated fats increase harmful bacteria and worsen glycemic control. Long-term imbalance in gut microbiota may also contribute to metabolic disorders such as **Obesity** and **Metabolic Syndrome**. In addition, gut microbiota reduces systemic inflammation, which is closely linked to glucose metabolism, as chronic inflammation interferes with insulin function and leads to elevated blood sugar levels. By reducing inflammation and improving insulin sensitivity, a healthy gut microbiota plays a protective role in maintaining glycemic balance.

Gut Microbiota and Its Impact on Blood Glucose Regulation

Diet (Fiber-rich foods, Prebiotics, Probiotics)

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Growth of Beneficial Gut Bacteria

↓

Fermentation of Fiber & Carbohydrates

↓

Production of Short Chain Fatty Acids (SCFAs)

(Acetate, Propionate, Butyrate)

↓

Improved Intestinal Barrier Function

↓

Reduced Inflammation in Body

↓

Increased Insulin Sensitivity

↓

Regulation of Glucose Absorption

↓

Hormone Release (GLP-1, PYY)

↓

Slower Gastric Emptying

↓

Controlled Blood Glucose

↓

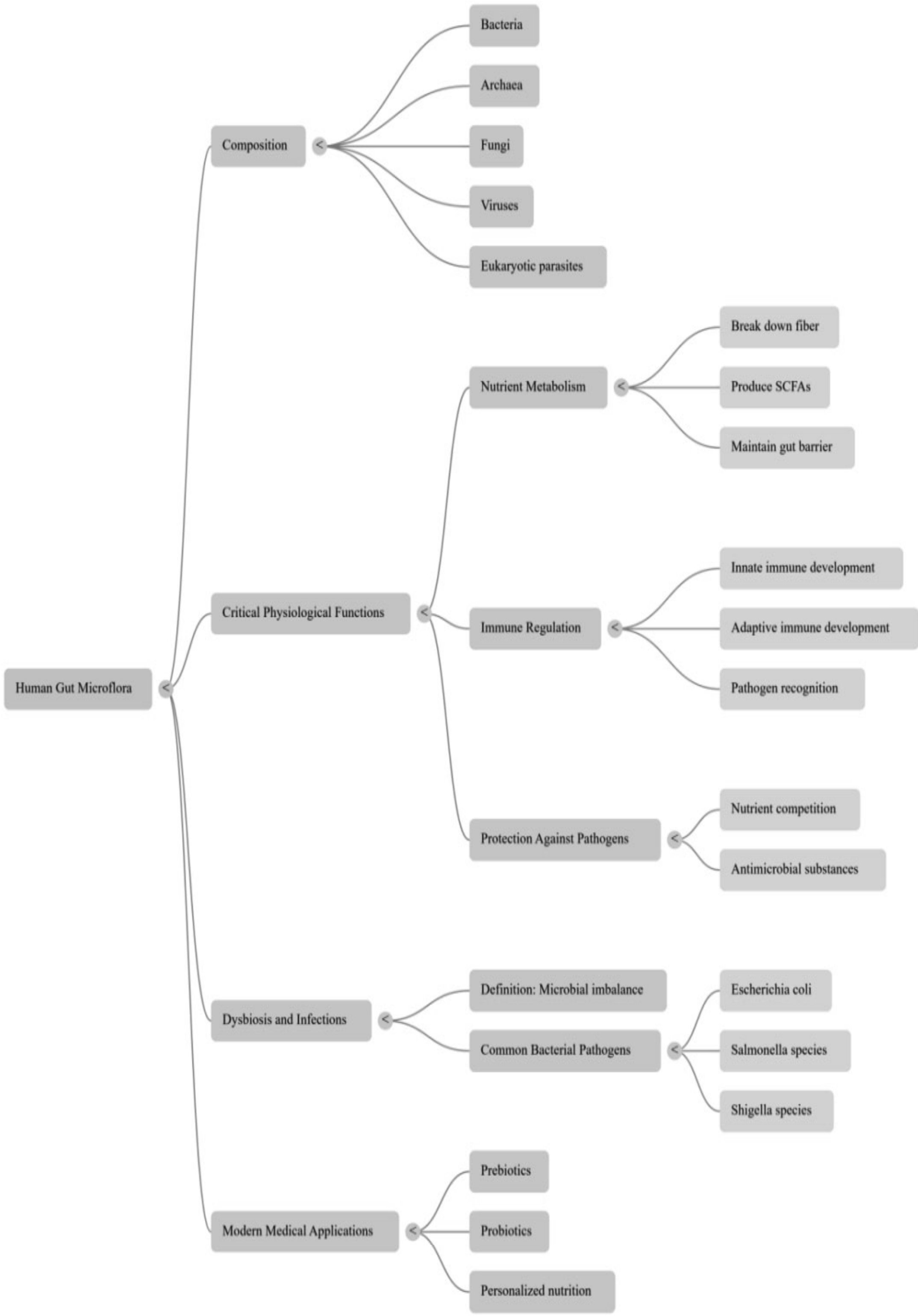
Good Glycemic Control

7.Improvement of Gut Microbiota

Improving gut microbiota is fundamental for maintaining proper digestion, strong immunity, and overall health, and one of the most effective ways to achieve this is through a balanced diet rich in dietary fiber—found in fruits, vegetables, whole grains, and legumes—which promotes the growth of beneficial bacteria that ferment fiber to produce short-chain fatty acids for intestinal health and nutrient absorption. Incorporating fermented foods such as yogurt, curd, buttermilk, and pickled vegetables further supports this balance by introducing live probiotics, while simultaneously reducing the consumption of processed foods, excess sugar, and unhealthy fats is essential to prevent the overgrowth of harmful bacteria linked to obesity and Type 2 diabetes. Beyond nutrition, proper hydration facilitates digestion and intestinal movement, and regular physical activity has been shown to improve microbial diversity and metabolic function. Furthermore, managing chronic stress through relaxation techniques and adequate sleep is crucial for protecting the gut-brain axis and preventing disorders like Irritable Bowel Syndrome, just as avoiding the unnecessary use of antibiotics preserves beneficial microbial populations. Ultimately, maintaining good hygiene, preventing infections, and following a holistic healthy lifestyle—including the use of probiotic-rich foods after necessary medical treatments—collectively support a resilient and balanced gut microbiota.

- A balanced diet is important for improving gut microbiota and maintaining overall health.
- Dietary fiber from fruits, vegetables, whole grains, and legumes promotes the growth of beneficial bacteria.
- Fiber is fermented by gut bacteria to produce short-chain fatty acids that support intestinal health.
- Probiotics help maintain microbial balance and improve digestion.
- Reducing processed foods helps prevent the growth of harmful bacteria.
- Limiting excess sugar and unhealthy fats reduces the risk of obesity and Type 2 diabetes.
- Proper hydration supports digestion and healthy bowel movement.
- Drinking adequate water helps maintain intestinal function.
- Regular physical activity improves gut microbial diversity and metabolic health.
- Exercise also helps regulate digestion and immune function.
- Managing stress is important for maintaining gut health.
- Chronic stress can negatively affect the gut-brain axis and digestive system.
- Adequate sleep supports gut microbiota balance and overall well-being.
- Avoiding unnecessary antibiotic use helps preserve beneficial bacteria.

- Maintaining good hygiene helps prevent infections that affect gut microbiota.
- Following a healthy lifestyle supports long-term gut microbial balance.
- Consuming probiotic-rich foods after medical treatments helps restore beneficial bacteria.


Human Gut Microflora
Composition
Bacteria
Archaea
Fungi
Viruses
Eukaryotic parasites
Critical Physiological Functions
Nutrient Metabolism
Break down fiber
Produce SCFAs
Maintain gut barrier
Immune Regulation
Innate immune development
Adaptive immune development
Pathogen recognition
Protection Against Pathogens
Nutrient competition
Antimicrobial substances
Dysbiosis and Infections
Definition: Microbial imbalance
Common Bacterial Pathogens
Escherichia coli
Salmonella species
Shigella species
Modern Medical Applications
Prebiotics
Probiotics
Personalized nutrition

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Physiotherapeutic Diabetes Rehabilitation

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As the global prevalence of diabetes mellitus continues to escalate, it has evolved into a critical public health challenge that necessitates a synergistic integration of pharmacological intervention and targeted physical rehabilitation (Gelaw, 2017). This metabolic disorder, primarily characterized by chronic hyperglycaemia resulting from defects in insulin secretion or action or both, demands a holistic strategy that transcends conventional glycaemic control to mitigate long-term microvascular and macrovascular complications (Alwabari et al., 2025). Clinical diagnosis typically involves-

- **Blood Glucose Monitoring:** The cornerstone of diagnosis and management is the assessment of elevated blood glucose levels (Mahgoub et al., 2023). Normal fasting plasma glucose values in children and adults are **3.3–5.6 mmol/L (60–100 mg/dL)** and **4.1–6.1 mmol/L (74–110 mg/dL)** respectively.
- **Glycated Haemoglobin (HbA1c):** This is a critical marker for long-term glycaemic control. Normal value should be **>5.7%** and pre-diabetic range is **5.7% to 6.4%** (American Diabetes Association, 2023)

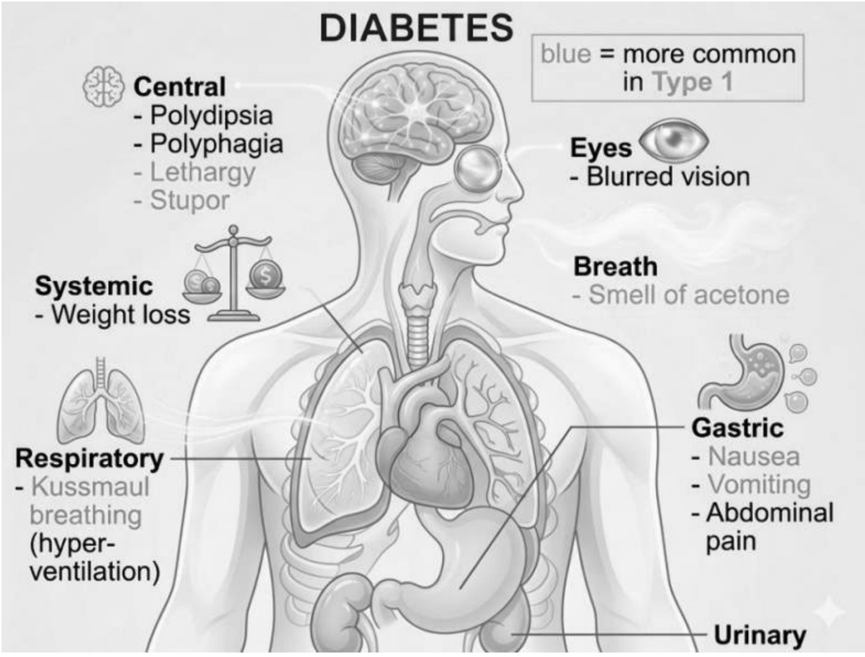
Recent epidemiological data indicates that approximately 536 million adults currently live with this condition, a figure projected to rise significantly as sedentary lifestyles and obesity continue to drive metabolic dysfunction (International Diabetes Federation, 2021). Given this high prevalence, physical therapists are uniquely positioned to intervene, as nearly 80% of patients referred to outpatient clinics either live with diabetes or reside within the high-risk spectrum.

Classification of Diabetes

Diabetes is classified into several types based on its underlying pathophysiology and etiology (American Diabetes Association, 2022)

Type	Primary Cause	Key Characteristics
Type 1 (T1DM)	Autoimmune destruction of pancreatic -cells	Absolute insulin deficiency; typically occurs in youth but can affect adults
Type 2 (T2DM)	Progressive insulin secretory defect on a background of insulin resistance	Most common form (90% of cases); strongly associated with obesity and metabolic syndrome
Gestational	Insulin resistance and glucose intolerance during pregnancy	First recognized during pregnancy; increases future risk of T2DM
Maturity-Onset Diabetes of the Young (MODY)	Monogenic genetic mutations affecting -cell function	Autosomal dominant inheritance; usually diagnosed before age 25; characterized by impaired secretion without insulin resistance
Latent Autoimmune Diabetes in Adults (LADA)/ Type 1.5	Latent autoimmune destruction of -cells in adults	Slow-progressing autoimmune diabetes, shares characteristics of both T1DM & T2DM in adults; often misdiagnosed initially as T2DM
Secondary/Other	Specific conditions or treatments	Caused by pancreatitis, cystic fibrosis, Cushing syndrome, or drug-induced (e.g., glucocorticoids)

Signs and Symptoms are-



T4 to remember type 1 diabetes

- Toilet
- Tiredness
- Thinner
- Thirsty

Symptoms of Hypo and hyperglycaemia

Hypoglycaemia	Hyperglycaemia
Fast heartbeat	Extreme thirst
Dizziness	Need to urinate often
Sweating	Dry skin
Shaking	Hungry
Anxious	Blurry vision
Hunger	Drowsy
Impaired vision	Slow healing wounds

Weakness fatigue **Headache** **Irritability**	

Associated Comorbidities

Diabetes frequently co-occurs with other conditions, which can accelerate the development of following complications (American Diabetes Association, 2024; Islam et al., 2025).

- **Nephropathy:** Chronic kidney disease and renal failure.
- **Retinopathy:** Eye disease leading to potential vision loss.
- **Neuropathy:** Peripheral nerve damage causing foot pain, numbness, or tingling.
- **Hypertension:** Present in over 50% of diabetic patients.
- **Dyslipidaemia:** High triglycerides, low HDL, and elevated LDL.
- **Obesity:** A primary driver and frequent comorbidity of T2DM.
- **Cardiovascular Disease:** Including ischemic heart disease, congestive heart failure, and *stroke*.
- **Peripheral Arterial Disease:** Leading to foot ulcers *(Diabetic Foot)* and potential *amputation*.
- **Diabetic Ketoacidosis**
- **Diabetic pneumopathy**
- **Acanthosis Nigricans:** Darkened skin patches, often a sign of severe insulin resistance.

Management of Diabetes

Pharmacological management is the primary clinical strategy for regulating the metabolic disturbances associated with diabetes, yet its impact on a patient's overall health is a double-edged sword that often necessitates complex polypharmacy. While foundational medications such as metformin are essential for glucose control and may even offer secondary benefits for conditions like erectile dysfunction or prostate health, they primarily target chemical imbalances rather than the underlying physical decline (Tseng, 2022). In reality, diabetic patients often face a heavy burden of medication to manage a cluster of comorbidities; for example, hypertension is present in over 50% of this population, requiring additional antihypertensive agents alongside lipid-lowering drugs for dyslipidaemia (Ashok et al., 2020; Tseng, 2022). Clinical analysis of prescription patterns for Type II Diabetes (T2DM) inpatients reveals that these multiple pharmacological interventions are necessary to reduce the risk of atherosclerotic cardiovascular disease, obesity-related complications, and severe metabolic crises (Ashok et al., 2020; Iglay et al., 2021). However, even when glycaemic targets—such as an HbA1C below 7.0%—are successfully met, patients still frequently experience debilitating secondary symptoms such as chronic neuropathic pain and a diminished quality of life that medication alone cannot fully resolve (Abu-Shennar et al., 2020; American Diabetes Association Professional Practice Committee, 2022). Furthermore, long-term pharmacological dependence does not prevent the development of musculoskeletal impairments, such as "frozen shoulder" or general upper extremity disability, which affect between 11% and 50% of the diabetic population and severely limit functional independence (Jagtap, 2024; Shah et al., 2014). Thus, while pharmacology is life-saving, it often leaves significant gaps in the patient's physical and functional recovery.

Physiotherapy effectively bridges this gap by offering a non-pharmacological means to restore metabolic health and functional capacity, essentially acting as a physiological countermeasure to the systemic damage of diabetes. Unlike drugs that chemically induce glucose uptake, structured exercise therapy—particularly the combination of aerobic and resistance training—naturally enhances insulin sensitivity and improves the body's primary glucose disposal sites in skeletal muscle (Benkar & Kanase, 2017). Evidence suggests that engaging in 30 minutes of aerobic activity at 60–84% of the maximal heart rate, combined with progressive resistance training 2–3 days per week, leads to significant reductions in HbA1c, triglycerides, and systemic cholesterol levels (Benkar & Kanase, 2017; Bhosale & Thangavelu, 2019).

Physiotherapy also uniquely addresses the neurological and musculoskeletal complications that medications cannot "cure"; for instance, specialized balance and gait training programs utilizing task-oriented motor exercises and visual feedback have been shown to improve composite equilibrium and significantly reduce the high risk of falls associated with peripheral neuropathy (Nardone et al., 2014; Stolarczyk et al., 2021). For those suffering from adhesive capsulitis, manual therapy techniques like joint mobilization and progressive strengthening exercises are far more effective than analgesics alone for restoring range of motion and reducing physical disability (Babu & Ramalingam, 2024; Jagtap, 2024; Walke & Telang, 2022). Ultimately, by integrating these physical interventions with lifestyle modifications, physiotherapy not only assists in achieving biochemical targets but also builds "balance confidence" and physical resilience, allowing patients to overcome the functional limitations and secondary health issues that pharmacological management alone cannot address (BHOSALE & Thangavelu, 2019; Venkataraman et al., 2019).

DIABETIC REHABILITATION

Goals of Diabetic Rehabilitation in Physiotherapy

Physiotherapy in diabetic rehabilitation aims to address the complex interplay of metabolic, neurological, and musculoskeletal impairments. The goals are:

- **Optimize Glycaemic Control:** Enhance insulin sensitivity and glucose metabolism through structured physical activity.
- **Restore and Preserve Functional Mobility:** Prevent and treat joint contractures, muscle weakness, and gait abnormalities to maintain independence.
- **Prevent and Manage Complications:** Reduce incidence of neuropathic ulcers, falls, cardiovascular deconditioning, and musculoskeletal deformities.
- **Enhance Cardiovascular and Muscular Fitness:** Counteract sedentary lifestyle effects and diabetes-induced muscle wasting.
- **Promote Patient Education and Self-Management:** Empower patients with knowledge and skills for ongoing disease management.
- **Support Psychological Well-being:** Address mental health issues such as depression and anxiety, which impact adherence and outcomes.

Comprehensive Assessment in Diabetic Rehabilitation

A thorough assessment is fundamental to devising effective rehabilitation plans. It encompasses multiple domains:

1. Medical and Diabetes History: assessment will be done through PHYSICAL ACTIVITY READINESS QUESTIONNAIRE (PAR-Q)

- Type and duration of diabetes
- Glycaemic control indicators (HbA1c, fasting glucose)
- Medication regimen and adherence

- Presence of comorbidities (hypertension, dyslipidaemia, cardiovascular disease)
- History of diabetic complications (neuropathy, retinopathy, nephropathy).

Par Q Form

Name: ______________________ Date: ______________________

Telephone: ______________________

Date of Birth:_______ Age: _________ Height: ____________ Weight:________

In Case of Emergency Contact: ______________________ Relationship:___________

Address: ______________________ Phone: _______

Physician: ______________________ Specialty: _______

Address: _______ Phone: _______

Are you currently under a doctor's care:	Yes ☐	No ☐
If yes, explain: ______________________		
When was the last time you had a physical examination? ______________________		
Have you ever had an exercise stress test:	Yes ☐ No ☐	Don't Know ☐
If yes, were the results:	Normal ☐	Abnormal ☐
Do you take any medications on a regular basis?	Yes ☐	No ☐
If yes, please list medications and reasons for taking: ______________________		
Have you been recently hospitalized?	Yes ☐	No ☐
If yes, explain: ______________________		
Do you smoke?	Yes ☐	No ☐
Are you pregnant?	Yes ☐	No ☐
Do you drink alcohol more than three times/week?	Yes ☐	No ☐
Is your stress level high?	Yes ☐	No ☐
Are you moderately active on most days of the week?	Yes ☐	No ☐
Do you have:		
High blood pressure?	Yes ☐	No ☐
High cholesterol?	Yes ☐	No ☐
Diabetes?	Yes ☐	No ☐
Have parents or siblings who, prior to age 55 had:	Yes ☐	No ☐
A heart attack?	Yes ☐	No ☐
A stroke?	Yes ☐	No ☐
High blood pressure?	Yes ☐	No ☐

2. Neurological Examination:

- Diabetic foot/stump assessment
- Diabetic neuropathy- DN4 questionnaire
- Sensory testing
- Reflex assessment: Achilles and patellar reflexes

- Motor strength: Manual muscle testing focusing on distal lower limb muscles through Handgrip Strength Test with Dynamometer, MMT, Arm Curl Test, Sit-against-wall test.
- Balance and proprioception: Berg Balance Scale, Timed Up and Go (TUG), Functional Reach Test, Dynamic gait index.

FOOT EXAMINATION PROTOCOL®

Date: Sign:	MARKERS OF RISK TO DEVELOP FOOT PROBLEMS					
DM type: Onset:	NEUROPATHY	R	L	ANGIOPATHY	R	L
Treatment:	Dry skin			Palpable foot pulses		
Smoker: present Y / N	Hair missing			Blood pressure (mmHg)		
previous Y / N	Oedema			Ankle pressure (mmHg)		
Impaired vision: Y / N	Warm skin			Pigmentation		
Right Left	Reduced sensibility (Monofilament 10g)			Rest pain		
	Reduced vibration (tuning fork 128Hz)			Walking pain (Claudicatio interm.)		
	Reduced big toe extension			Discoloured skin blue/red		
	Deformity			Cold skin		
	Biothesiometer max (V) min			HbA1c % Reference (<)		

If above parameters are present write Y=Yes, N=No (R=Right, L=Left)

0 wound

/// redness

heal cracks

XX callus

osteopathy

ØØ other……………………………

……………………………………

……………………………………

	Date
Foot ulcer now: Since	
Previous foot ulcer	
Orthopaedic shoes since	
Supportive insoles:	
Amputation:	
Toe	
Foot	
Below knee	
Above knee	
Regular chiropody Y/N	

Risk classification

Group 1

Group 2

Group 3

GROUP 1: (Low risk) No registered foot complication
GROUP 2: (Middle risk) Registered signs of peripheral neuropathy: dry skin, reduced hair on the foot, warm skin, reduced sensibility, callus (hyperkeratosis) and often foot deformities sometimes stiff joints
GROUP 3: (High risk) Previous and present foot ulcer and/or a combination of neuropathy and micro/macroangiopathy.

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DN4 Questionnaire

Name: ____________________ **Age:** __________

Gender: ◯ Male ◯ Female ◯ Other: __________ **Date:** __________

To estimate the probability of neuropathic pain, please answer yes or no for each item of the following four questions.

Interview of the patient			
Question 1: Does the pain have one or more of the following characteristics?			
Burning ◯ Yes ◯ No	Painful cold ◯ Yes ◯ No	Electric shocks ◯ Yes ◯ No	
Question 2: Is the pain associated with one or more of the following symptoms in the same area?			
Tingling ◯ Yes ◯ No	Pins and needles ◯ Yes ◯ No	Numbness ◯ Yes ◯ No	Itching ◯ Yes ◯ No
Examination of the patient			
Question 3: Is the pain located in an area where the physical examination may reveal one or more of the following characteristics?			
Hypoesthesia to touch ◯ Yes ◯ No	Hypoesthesia to pinprick ◯ Yes ◯ No		
Question 4: In the painful area, can the pain be caused or increased by: Brushing? ◯ Yes ◯ No			
YES = 1 point **NO** = 0 point			
Patient's score:			

Reference:

Agency for Clinical Innovation. DN4 Questionnaire. https://aci.health.nsw.gov.au/__data/assets/pdf_file/0014/212900/DN4_Assessment_Tool.pdf

3. Musculoskeletal Evaluation:

- Body composition assessment- Waist circumference, and Body Mass Index (BMI) above 30 is obese and 35 is morbid (weight/ height^2)
- Joint range of motion- goniometry, focusing on hands, shoulders, ankles, and feet
- Muscle flexibility and tone assessment
- Identification of contractures, deformities (hammer toes, Charcot foot)
- Postural analysis and gait observation

4. Functional Capacity:

- Activities of Daily Living (ADL) assessment- Quality of life questionnaire, pedometers and accelerometers.

5. Cardiopulmonary Fitness:

- Resting heart rate and blood pressure- following guidelines should be used:
- The patient should not consume caffeine-containing drinks or smoke.
- Cigarettes for at least 30 minutes before assessment.
- No exercises should have been performed for at least 30 minutes before assessment, and blood pressure should be measured at least twice (with averaging of results
- submaximal or maximal exercise capacity- 6-Minute Walk Test (6MWT), sit to stand test, Cardiopulmonary exercise testing (CPET)
- Autonomic function tests to check orthostatic hypotension.
- SPO2
- Arterial Blood Gas analysis (if symptoms persists).
- Modified Borg dyspnoea scale & rate of perceived exertion.
- Pulmonary function test.

6. Psychosocial Screening:

- Assessment for depression and anxiety (using validated scales)

- Evaluation of motivation, social support, and barriers to rehabilitation

Physiotherapy Interventions in Diabetic Rehabilitation

1. Exercise Therapy

Exercise therapy is the cornerstone of diabetic rehabilitation, with multifaceted benefits spanning metabolic, cardiovascular, neuromuscular, and psychological domains.

Aerobic Exercise:

Moderate-intensity aerobic exercise, such as brisk walking, cycling, or swimming, performed for at least 150 minutes per week, has demonstrated significant reductions in HbA1c (0.6–0.7%) and improvements in cardiovascular health. Exercise intensity should be personalized based on baseline fitness and cardiovascular risk, monitored using heart rate, perceived exertion scales, or wearable devices. Aerobic training enhances endothelial function, reduces inflammation, and promotes weight management.

Resistance Training:

Resistance or strength training, conducted 2–3 times weekly, targets major muscle groups to increase muscle mass, improve insulin sensitivity, and counteract sarcopenia. Progressive overload principles should guide training intensity, with initial low loads advancing as tolerated. Resistance training improves functional independence by enhancing strength for ADLs and reducing fall risk.

Flexibility Exercises:

Regular stretching maintains joint mobility, prevents contractures, and reduces musculoskeletal pain. Emphasis should be placed on commonly affected areas such as the hands (to mitigate cheiroarthropathy), shoulders, and lower limbs. Stretching protocols include static and dynamic techniques, performed daily or at least thrice weekly.

Balance and Proprioception Training:

Peripheral neuropathy impairs balance and proprioception, increasing fall risk. Balance training includes static postures (single-leg stance), dynamic activities (tandem walking, obstacle courses), and use of unstable surfaces (balance boards, foam pads). Incorporating dual-task exercises (cognitive and motor tasks) enhances neuroplasticity and functional stability.

Combined Exercise Programs:

Integrated programs combining aerobic, resistance, flexibility, and balance training yield synergistic improvements in metabolic control, physical function, and quality of life. Tailoring exercise selection, intensity, and progression to individual needs is essential.

2. Neuromuscular Rehabilitation

Peripheral neuropathy requires specialized neuromuscular strategies to restore function and prevent complications.

Sensory Re-education:

Techniques such as graded tactile stimulation, vibration therapy, and mirror therapy aim to enhance sensory discrimination and protective sensation. Sensory re-education improves patient awareness of limb position and potential injury, reducing ulcer risk.

Motor Re-education:

Strengthening intrinsic foot and lower limb muscles improves motor control, foot stability, and gait mechanics. Exercises include toe curls, ankle dorsiflexion/plantarflexion against resistance, and functional weight-bearing tasks.

Gait Training:

Abnormal gait patterns due to neuropathy and musculoskeletal changes increase plantar pressure and ulcer risk. Task-specific gait training focuses on heel-to-toe walking, step symmetry, and cadence normalization. Use of assistive devices (canes, walkers) and orthotics (custom insoles, ankle-foot orthoses) supports safe ambulation.

Visual Feedback and Biofeedback: The use of computerized posturography and visual feedback training has proven effective in improving composite equilibrium scores and reducing fall risk in patients with mild to moderate neuropathy (Nardone et al., 2014).

3. Wound Care and Ulcer Prevention

Diabetic foot ulcers (DFUs) are a major cause of morbidity and hospitalization. Physiotherapists contribute significantly to multidisciplinary wound management.

Pressure Offloading:

Diabetic patients must understand how to pre-emptively prevent foot complications. There have been significant advancements in the treatment of diabetic foot. However, prevention is the effective strategy to prevent complications.

When it comes to foot care, footwear and orthotics are essential. Patients with diabetes must learn how to properly inspect their own feet and identify the early warning signs and symptoms of diabetic foot issues. Therefore, it is paramount to educate diabetics about appropriate footwears. The finest substance to protect a diabetic foot is plastazote foam. In addition to offering comfort and protection, this material is designed to adapt to pressure and heat. Additionally, diabetic shoes should have rocker soles to reduce pressure, heel counters to offer stability and support, a high, wide toe box to expand space and reduce pressure, and detachable insoles to implant orthotics (Bus et al., 2020).

Therapeutic Modalities:

Adjunctive therapies such as electrical stimulation, ultrasound, and low-level laser therapy promote angiogenesis, collagen synthesis, and wound closure. Modalities are applied as per wound characteristics and patient tolerance.

Safe Mobilization:

Balancing mobility to enhance circulation with ulcer protection is essential. Weight-bearing is gradually reintroduced under supervision, with emphasis on gait retraining and use of assistive devices to minimize ulcer stress.

Hyperbaric oxygen therapy:

Hyperbaric oxygen therapy involves breathing 100% oxygen at high atmospheric pressure, which enhances oxygen levels in human cells to significantly accelerate the healing of chronic diabetic foot ulcers (Sharma et al., 2021).

Ozone therapy:

Ozone therapy acts as a potent antibacterial and antioxidant agent that stimulates endogenous growth factors to promote rapid wound closure in diabetic patient (Zhang et al., 2014).

4. Cardiopulmonary Rehabilitation

Cardiovascular disease is the leading cause of mortality in diabetes. Physiotherapy integrates cardiac rehabilitation principles to mitigate risk.

Structured Exercise Prescription:

Exercise programs are individualized based on cardiovascular risk stratification, incorporating aerobic and resistance training with gradual progression. Continuous monitoring for hypoglycaemia, arrhythmias, or ischemic symptoms is mandatory.

Breathing Exercises:

Diaphragmatic breathing and inspiratory muscle training improve respiratory efficiency, especially in patients with autonomic neuropathy or sedentary lifestyles.

Lifestyle Counselling:

Physiotherapists provide education on smoking cessation, dietary modifications, and medication adherence as part of comprehensive cardiovascular risk management.

5. Pain Management

Chronic neuropathic and musculoskeletal pain significantly impair function and quality of life.

Transcutaneous Electrical Nerve Stimulation (TENS):

TENS modulates nociceptive signalling, providing non-pharmacological analgesia. Parameters are individualized based on pain characteristics.

Manual Therapy:

Soft tissue mobilization, joint mobilizations, and myofascial release alleviate pain, improve circulation, and enhance tissue extensibility.

Therapeutic Ultrasound:

Ultrasound therapy reduces inflammation and promotes tissue repair in musculoskeletal pain syndromes.

Cognitive-Behavioural Strategies:

Education on pain mechanisms and coping strategies reduces pain-related disability and enhances rehabilitation adherence.

6. Patient Education and Self-Management

Sustainable rehabilitation outcomes depend on patient empowerment.

Exercise Guidelines:

Patients are trained to monitor blood glucose before and after exercise, recognize hypoglycaemia and hyperglycaemia symptoms, and adjust activity accordingly.

Lifestyle Modification:

Counselling on balanced nutrition, weight management, smoking cessation, and stress reduction supports comprehensive care.

Foot Care Education:

Daily foot inspection, hygiene, and early identification of skin changes are emphasized to prevent ulcers.

Psychosocial Support:

Motivational interviewing and addressing barriers such as depression or social isolation enhance adherence.

The FITT principle is the standard framework used in physiotherapy to prescribe exercise for diabetic patients. Structured interventions are designed to maximize glucose uptake while minimizing the risk of exercise-induced complications (Gelaw, 2018).

FITT Exercise Guidelines for Diabetes

Physiotherapy evidence-based protocols emphasize a multi-modal approach to improve both metabolic markers and physical functional status (Venkataraman et al., 2019).

Component	**Guideline**	**Details & Evidence**
Frequency	3–7 days/week	Aerobic exercise should be performed at least 3–5 days per week; resistance training 2–3 days per week (Benkar & Kanase, 2017; Gelaw, 2018).
Intensity	60–84% of Max HR	Moderate to vigorous intensity is recommended for aerobic tasks; resistance should be progressive using weight cuffs or dumbbells (Benkar & Kanase, 2017).

Time	30–60 minutes	Continuous or accumulated sessions totalling at least 150 minutes of moderate activity per week (Gelaw, 2018).
Type	Combined Training	A mixture of aerobic (walking, jogging, cycling) and resistance (strength training) is more effective than either alone (Benkar & Kanase, 2017; Gelaw, 2018).

Exercise Guidelines for Type 1 Diabetes (T1DM)

In T1DM, the primary focus of physiotherapy is to improve cardiovascular fitness and maintain metabolic stability without causing severe hypoglycaemia or ketoacidosis (Riddell et al., 2017)

- **Glucose Monitoring:** Patients must monitor blood glucose before, during, and after exercise. If pre-exercise glucose is **< 100 mg/dL**, carbohydrate intake is required to prevent exercise-induced hypoglycaemia (Standards of Care in Diabetes—2023 Abridged for Primary Care Providers,2022).
- **Hypoglycaemia Prevention:** Resistance training should ideally be performed *before* aerobic activity in a session, as this sequence has been shown to result in less hypoglycaemia in T1DM patients (Gelaw, 2018).
- **Contraindications:** Exercise must be avoided if blood glucose is **> 250 mg/dL** with ketones present, as physical activity can exacerbate ketosis in an insulin-deficient state (Gelaw, 2018).
- **Intensity Adjustments:** Moderate intensity is generally safer; high-intensity intervals may cause transient hyperglycaemia due to the surge of counter-regulatory hormones (Gelaw, 2018).

Exercise Guidelines for Type 2 Diabetes (T2DM)

For T2DM, the physiotherapy objective is to reduce insulin resistance, manage weight, and address chronic co-morbidities like hypertension and neuropathy (Bhosale & Thangavelu, 2019; Ranjani & Mahalakshmi, 2022). Follow HRmax (220-age) or Karvonen equation ((Max HR − Resting HR) × %Intensity) + Resting HR and avoid Valsalva manoeuvre. Maintain the blood pressure under 220/105 while exercising.

- **Insulin Sensitivity:** Combined aerobic and resistance training is the gold standard, significantly reducing HbA1c, total cholesterol, and triglycerides (Bhosale & Thangavelu, 2019; Vanderstraeten, 2008). Resistance training (2–3 sets of 8–12 repetitions) is crucial for increasing the muscle mass required for glucose disposal (Benkar & Kanase, 2017).
- **Neurological Safety:** For patients with Peripheral Neuropathy, weight-bearing exercise must be monitored for foot trauma. Task-oriented balance training and visual feedback exercises are integrated to improve equilibrium and reduce fall risk (Stolarczyk et al., 2021).
- **Consistency:** Patients should not go more than two consecutive days without physical activity to maintain the acute improvements in insulin action (Gelaw, 2018).
- **Musculoskeletal Care:** Since T2DM is highly associated with adhesive capsulitis, protocols often include joint mobilization or manual stretching to restore the range of motion in the shoulder (Babu & Ramalingam, 2024; Jagtap, 2024).

By following these tailored guidelines, physiotherapists can safely assist patients in achieving a significant reduction in medication dependency and an overall improvement in functional status (Venkataraman et al., 2019).

Latest Research and Advances in Diabetic Rehabilitation

Recent innovations emphasize technology integration and personalized care.

Tele-rehabilitation:

Remote physiotherapy via video conferencing and wearable sensors enables continuous monitoring, improves adherence, and extends care to underserved populations. Studies demonstrate comparable clinical outcomes and increased patient satisfaction.

High-Intensity Interval Training (HIIT):

HIIT protocols, involving brief bursts of high-intensity exercise interspersed with recovery, have shown superior improvements in glycaemic control, cardiovascular fitness, and mitochondrial function compared to moderate continuous training. Adaptability makes HIIT suitable for diverse patient profiles.

Virtual Reality (VR) and Gamification:

Immersive VR environments and gamified exercises increase patient engagement and neuroplasticity, particularly in balance and motor training. These technologies enhance motivation and functional gains, especially in elderly or cognitively impaired patients.

Regenerative Therapies:

Emerging research explores combining physiotherapy with stem cell therapy, growth factors, and advanced wound dressings to accelerate tissue repair in diabetic ulcers, though clinical application remains investigational.

Multidisciplinary Integrated Care:

Coordinated care involving endocrinologists, podiatrists, dietitians, psychologists, and physiotherapists optimizes outcomes, reduces hospitalizations, and enhances patient-centred management.

Wearable Technology and Artificial Intelligence:

Continuous glucose monitors, activity trackers, and AI-driven analytics enable real-time feedback and personalized rehabilitation adjustments, fostering proactive disease management.

Challenges and Considerations in Diabetic Rehabilitation

Patient Adherence:

Fear of hypo and hyperglycaemia, lack of motivation, depression, and social isolation hinder consistent participation in rehabilitation programs.

Comorbidities:

Cardiovascular disease, obesity, musculoskeletal disorders, and autonomic neuropathy complicate exercise prescription and necessitate cautious progression.

Resource Limitations:

Access to specialized physiotherapy services may be limited in rural or low-resource settings, necessitating innovative delivery models such as tele-rehabilitation.

Individual Variability:

Heterogeneity in diabetes severity, complication profiles, and patient preferences requires flexible, patient-centred approaches.

Safety Concerns:

Risk of hypo and hyperglycaemia, foot ulcers, and cardiovascular events mandates vigilant monitoring and risk stratification.

Addressing these challenges requires multidisciplinary collaboration, patient education, and leveraging technology to enhance accessibility and adherence.

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Functional Foods and Nutraceuticals in Diabetes Management

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Abstract

Diabetes mellitus is a multifactorial metabolic disorder characterized by chronic hyperglycemia arising from impaired insulin secretion, insulin resistance, or both. Increasing evidence supports the role of functional foods and nutraceuticals as targeted dietary interventions capable of modulating key biochemical pathways involved in glucose metabolism. Unlike conventional dietary strategies, these interventions provide specific bioactive compounds that directly influence insulin signaling, glucose uptake, oxidative stress, inflammation and gut microbiota. This chapter presents a highly focused, mechanism-driven analysis of functional foods and nutraceuticals, emphasizing their specific roles, bioactive constituents and clinical relevance in diabetes management.

Introduction

The pathogenesis of diabetes involves multiple interconnected metabolic disturbances, including impaired insulin sensitivity, progressive pancreatic β-cell dysfunction, enhanced hepatic glucose output, chronic inflammation, and oxidative stress. These alterations occur simultaneously and interact in a complex and self-amplifying manner, thereby accelerating disease progression and increasing the risk of complications. Insulin resistance in peripheral tissues such as skeletal muscle and adipose tissue reduces glucose uptake, while β-cell dysfunction limits insulin secretion, creating a dual defect that sustains hyperglycemia. In parallel, increased hepatic gluconeogenesis further contributes to elevated blood glucose levels, particularly during fasting conditions. Chronic low-grade inflammation and oxidative stress exacerbate these abnormalities by impairing insulin signaling pathways and damaging pancreatic β-cells.[1]

Given this multifaceted nature of diabetes, interventions that act on a single pathway are often insufficient for achieving optimal metabolic control. This has led to increased scientific interest in functional foods and nutraceuticals, which possess the unique ability to simultaneously modulate multiple targets within the diabetic cascade. These dietary components are rich in bioactive molecules such as polyphenols, dietary fibers, phytochemicals, and bioactive peptides that exert specific biochemical effects at cellular and molecular levels. For instance, certain polyphenols enhance insulin receptor sensitivity and activate intracellular signaling pathways such as AMP-activated protein kinase (AMPK), thereby improving glucose uptake and reducing hepatic glucose production [4]. Similarly, soluble fibers regulate glucose absorption kinetics and influence gut-derived metabolic signaling through short-chain fatty acid production.[3]

Unlike generalized dietary recommendations that focus on caloric restriction or macronutrient balance, functional foods and nutraceuticals emphasize the role of individual bioactive compounds in targeting defined metabolic defects. This mechanism-oriented approach allows for more precise modulation of disease pathways, including reduction of oxidative stress through antioxidant activity, suppression of inflammatory mediators via inhibition of transcription factors such as NF-κB, and improvement of insulin signaling through enhanced receptor function and glucose transporter activity. Consequently, the integration of functional foods and nutraceuticals into dietary strategies represents a shift toward a more targeted, evidence-based, and physiologically relevant approach to diabetes management [1].

Unlike conventional dietary approaches that focus primarily on macronutrient distribution, functional foods emphasize the presence of bioactive compounds that exert physiological effects beyond basic nutrition. Nutraceuticals, which are concentrated forms of such bioactives, provide targeted and measurable biological actions. Together, they offer a scientifically relevant and sustainable approach to long-term glycemic control.

Functional Foods in Diabetes

Functional foods exert significant effects on glucose metabolism through both their physicochemical properties and the presence of biologically active compounds that interact with digestive processes and cellular metabolic pathways. These foods influence glycemic regulation at multiple levels, including modulation of carbohydrate digestion, glucose absorption, insulin signaling, and gut-mediated metabolic responses.

Whole grains, particularly oats and barley, represent well-established functional foods in diabetes management due to their high content of β-glucan, a viscous soluble dietary fiber. Upon ingestion, β-glucan forms a gel-like matrix within the gastrointestinal lumen, increasing the viscosity of intestinal contents. This increased viscosity delays gastric emptying and limits the interaction between digestive enzymes and starch substrates, thereby reducing the rate of carbohydrate digestion and subsequent glucose absorption. Consequently, postprandial glycemic excursions are significantly attenuated.[15]

In addition to these physicochemical effects, β-glucan undergoes fermentation by colonic microbiota, resulting in the production of short-chain fatty acids (SCFAs), including acetate, propionate, and butyrate. These metabolites function as key signaling molecules that influence host metabolism. SCFAs enhance insulin sensitivity, modulate the secretion of incretin hormones such as glucagon-like peptide-1 (GLP-1), and suppress hepatic gluconeogenesis. Through these combined mechanisms, β-glucan–rich functional foods contribute to improved glycemic control and metabolic homeostasis in individuals with diabetes.[3]

Polyphenols- Rich Functional Foods

These foods play a critical role in diabetes management through their ability to modulate multiple molecular pathways associated with glucose homeostasis, oxidative stress, and inflammation. These bioactive compounds, abundantly found in fruits, vegetables, tea, cocoa, and whole grains, include flavonoids, phenolic acids, and stilbenes.At the cellular level, polyphenols enhance insulin sensitivity by improving insulin receptor signaling and activating AMP-activated protein kinase (AMPK), a central regulator of energy metabolism. Activation of AMPK promotes glucose uptake in skeletal muscle via increased translocation of glucose transporter type 4 (GLUT4) and suppresses hepatic gluconeogenesis. In addition, polyphenols inhibit key carbohydrate-digesting enzymes such as α-amylase and α-glucosidase, thereby attenuating postprandial hyperglycemia.

Recent evidence further indicates that polyphenols exert prebiotic-like effects by modulating gut microbiota composition and function, leading to improved metabolic outcomes. These interactions reduce inflammatory responses and contribute to enhanced insulin sensitivity. Moreover, their antioxidant properties mitigate oxidative stress by neutralizing reactive oxygen species (ROS) and enhancing endogenous antioxidant defenses. This protects pancreatic β-cells from oxidative damage and preserves insulin secretion. Polyphenols also suppress inflammatory signaling pathways, particularly nuclear factor kappa B (NF-κB), thereby reducing cytokine-mediated insulin resistance. Collectively, these mechanisms highlight their multi-targeted therapeutic potential in diabetes management. [1][2]

Probiotics and Gut Microbiota Modulation

The gut microbiota is recognized as a key regulator of metabolic homeostasis, and functional foods containing probiotics play an essential role in modulating microbial composition and activity. Probiotics, present in fermented foods such as yogurt and kefir, promote the growth of beneficial microbial populations and improve gut barrier integrity.This enhancement in intestinal barrier function reduces the translocation of endotoxins such as lipopolysaccharides (LPS), thereby lowering systemic inflammation and improving insulin sensitivity. Probiotic-induced modulation of gut microbiota also increases the production of short-chain fatty acids (SCFAs), which regulate glucose metabolism and stimulate incretin hormone secretion, including glucagon-like peptide-1 (GLP-1).

Recent studies have highlighted specific microbial species, such as *Akkermansia muciniphila*, which are associated with improved metabolic profiles, reduced insulin resistance, and decreased inflammation in experimental models. Additionally, gut microbiota influences bile acid metabolism and host signaling pathways involved in energy homeostasis. Through these integrated mechanisms, probiotic-rich functional foods contribute to improved glycemic regulation and represent a promising adjunct in diabetes management.[7]

Functional Spices and Bioactive Phytochemicals

Culinary spices constitute an important category of functional foods due to their high concentration of bioactive phytochemicals with antidiabetic properties. Spices such as cinnamon, turmeric, fenugreek, and ginger exert beneficial effects through diverse biochemical mechanisms.Cinnamon contains polyphenolic compounds that enhance insulin receptor activity and promote glucose uptake via GLUT4 translocation. Turmeric, rich in curcumin, exhibits potent anti-inflammatory and antioxidant effects by inhibiting NF-κB signaling and reducing oxidative stress. Fenugreek contains soluble fiber and 4-hydroxyisoleucine, which improve insulin secretion and delay carbohydrate absorption, while ginger-derived compounds (gingerols and shogaols) enhance insulin sensitivity and reduce inflammatory mediators.

Recent studies also indicate that phytochemicals present in spices can modulate multiple signaling pathways, including AMPK, thereby improving glucose metabolism and reducing insulin resistance. Thus, functional spices represent accessible and cost-effective dietary interventions with significant therapeutic potential in diabetes management [7].

Millets, Legumes and Plant Based Functional Foods in Diabetes Management

Millets, including finger millet (*Eleusine coracana*) and foxtail millet (*Setaria italica*), constitute an important class of functional foods with well-documented antidiabetic properties. Their low glycemic index facilitates a gradual release of glucose into the bloodstream, thereby minimizing postprandial glycemic fluctuations. In addition, millets are rich in polyphenolic compounds, which confer significant metabolic advantages.

These polyphenols inhibit key carbohydrate-digesting enzymes, including α-amylase and α-glucosidase, thereby reducing the rate of starch hydrolysis and subsequent glucose absorption. Beyond their effects on digestion, millet-derived phenolic compounds exert direct cellular actions by enhancing insulin receptor phosphorylation and activating downstream signaling pathways involved in glucose metabolism. This includes the promotion of glucose transporter type 4 (GLUT4) translocation to the plasma membrane in skeletal muscle and adipose tissues, facilitating increased glucose uptake and improved glycemic control [5].

Legumes represent another critical group of functional foods that contribute to diabetes management through their unique macronutrient composition and structural characteristics. They are rich in resistant starch, plant protein, and fermentable dietary fiber, which collectively modulate glycemic response. The dense starch–protein matrix of legumes limits enzymatic accessibility, resulting in delayed carbohydrate digestion and a sustained release of glucose into circulation.Furthermore, fermentation of resistant starch in the colon leads to the production of short-chain fatty acids (SCFAs), which play a regulatory role in metabolic pathways associated with insulin sensitivity, inflammation, and energy homeostasis. These effects are further supported by the presence of essential micronutrients and bioactive peptides that enhance metabolic regulation and insulin function [6].

Similarly, fruits and green leafy vegetables rich in flavonoids and other polyphenolic compounds provide protective effects against oxidative stress, a major contributor to pancreatic β-cell dysfunction in diabetes. These bioactive compounds neutralize reactive oxygen species and upregulate endogenous antioxidant systems, thereby preserving β-cell integrity. In addition, they activate key intracellular pathways, including AMP-activated protein kinase (AMPK), which enhances glucose uptake, improves insulin sensitivity, and supports cellular energy balance [7].

Collectively, millets, legumes, fruits, and green leafy vegetables exemplify plant-based functional foods that exert multifaceted effects on glucose metabolism. Through coordinated actions on digestive processes, cellular signaling pathways, and oxidative stress modulation, these foods contribute significantly to the dietary management of diabetes

Table 1: Functional Foods and Their Specific Roles in Diabetes

Functional Food	**Key Bioactive**	**Mechanistic Target**	**Detailed Mechanism of Action**	**Specific Role in Diabetes**
Oats	β-glucan	Intestinal viscosity	Forms gel matrix, delays gastric emptying, reduces enzymatic starch hydrolysis, slows glucose diffusion	Reduces postprandial glucose spikes and improves glycemic control
Barley	β-glucan	Gut fermentation (SCFA)	Fermentation produces SCFAs (butyrate, propionate) which enhance insulin sensitivity and regulate hepatic glucose output	Improves insulin sensitivity and reduces fasting glucose
Finger millet	Polyphenols (ferulic acid)	Digestive enzymes	Inhibits α-amylase and α-glucosidase, delaying carbohydrate digestion and glucose release	Reduces glucose absorption and postprandial hyperglycemia
Foxtail millet	Fiber + phenolics	Glycemic regulation	Slow starch digestibility and phenolic-mediated enzyme inhibition reduce glycemic load	Maintains stable blood glucose levels
Legumes	Resistant starch	Gut microbiota	Fermentation produces SCFAs, improves insulin	Enhances insulin sensitivity and

		and SCFA	signaling and reduces inflammation	metabolic control
Apple	Quercetin	AMPK pathway	Activates AMPK, promotes GLUT4 translocation and improves cellular glucose uptake	Enhances glucose utilization and reduces blood glucose
Leafy vegetables	Polyphenols	Antioxidant defense	Scavenges reactive oxygen species and protects pancreatic β-cells from oxidative damage	Reduces oxidative stress and preserves insulin secretion
Flaxseeds	Alpha-linolenic acid, lignans	Anti-inflammatory pathways	Modulates lipid metabolism, reduces inflammation, improves insulin sensitivity	Supports glycemic control and cardiovascular health
Chia seeds	Soluble fiber, omega-3	Gel formation, delayed absorption	Forms viscous gel, slows carbohydrate digestion and glucose absorption	Reduces postprandial glycemia
Moringa leaves	Polyphenols, isothiocyanates	Enzyme inhibition, antioxidant	Inhibits α-amylase/α-glucosidase, reduces oxidative stress	Lowers blood glucose and improves insulin response
Garlic	Allicin	Insulin signaling	Enhances insulin secretion and improves sensitivity	Reduces fasting glucose levels
Green tea	Catechins (EGCG)	AMPK activation	Enhances glucose uptake and fat oxidation	Improves insulin sensitivity

Nutraceuticals in Diabetes

Nutraceuticals represent a class of bioactive-rich compounds delivered in concentrated forms, allowing for precise and targeted modulation of metabolic pathways involved in diabetes. Unlike whole functional foods, which exert combined and sometimes diffuse effects, nutraceuticals provide specific active constituents at physiologically effective doses, thereby enabling measurable therapeutic outcomes. Among these, fenugreek has been extensively studied for its hypoglycemic properties, primarily attributed to the presence of 4-hydroxyisoleucine. This amino acid derivative directly stimulates insulin secretion from pancreatic β-cells, thereby enhancing endogenous insulin availability. In addition, fenugreek contains galactomannan, a soluble fiber that forms a viscous matrix in the gastrointestinal tract, slowing carbohydrate digestion and glucose absorption, which collectively contributes to improved postprandial glycemic control [7] .

Bitter gourd (Momordica charantia) functions as a potent insulin mimetic due to bioactive compounds such as charantin, vicine, and polypeptide-p. These compounds enhance peripheral glucose utilization by promoting glucose transporter translocation and increasing glycogen synthesis in muscle and hepatic tissues. Furthermore, bitter gourd has been shown to modulate key enzymes involved in glucose metabolism, including those regulating glycolysis and gluconeogenesis, thereby reducing circulating glucose levels [7].

Cinnamon exerts its antidiabetic effects through polyphenolic compounds such as cinnamaldehyde and procyanidins, which improve insulin receptor sensitivity and enhance downstream signaling pathways. This results in increased cellular glucose uptake and improved glycogen storage. Additionally, cinnamon inhibits intestinal α-glucosidase activity, thereby delaying carbohydrate digestion and attenuating postprandial hyperglycemia [8].

Curcumin and resveratrol represent multi-target nutraceuticals with broad-spectrum metabolic effects. Curcumin exerts strong anti-inflammatory action by inhibiting nuclear factor-kappa B (NF-κB), leading to decreased production of pro-inflammatory cytokines such as TNF-α and IL-6. This reduction in inflammation improves insulin signaling and protects pancreatic β-cells from oxidative damage [9]. Resveratrol, on the other hand, activates sirtuin 1 (SIRT1) and AMP-activated protein kinase (AMPK), key regulators of cellular energy metabolism. Activation of these pathways enhances mitochondrial function, increases glucose uptake in peripheral tissues, and suppresses hepatic glucose production, thereby improving overall metabolic homeostasis [10].

Berberine is one of the most potent nutraceuticals in diabetes management due to its strong AMPK-activating properties. Through this mechanism, it reduces hepatic gluconeogenesis, enhances glucose uptake in skeletal muscle, and improves insulin receptor expression. Additionally, berberine has been shown to modulate gut microbiota composition, which further contributes to improved metabolic regulation. Its multifaceted mechanism of action closely parallels that of metformin, positioning it as a promising natural therapeutic agent for glycemic control [11].

Table 2: Nutraceuticals and Their Targeted Mechanisms in Diabetes

Nutraceutical	Active Compound	Molecular Target	Specific Effect
Fenugreek	4-hydroxyisoleucine	β-cell stimulation	Increases insulin secretion
Bitter gourd	Charantin	Insulin mimicry	Enhances glucose uptake
Cinnamon	Polyphenols	Insulin receptor	Improves insulin sensitivity
Curcumin	Curcuminoids	NF-κB	Reduces inflammation
Resveratrol	Stilbenes	SIRT1/AMPK	Improves metabolism
Berberine	Alkaloid	AMPK	Reduces gluconeogenesis
Alpha-lipoic acid	Dithiol compound	Antioxidant/AMPK	Improves insulin sensitivity and reduces oxidative stress
Chromium picolinate	Trace mineral	Insulin receptor signaling	Enhances insulin action and glucose tolerance
Magnesium	Mineral	Insulin signaling enzymes	Improves insulin sensitivity
Zinc	Trace element	Insulin synthesis/storage	Supports insulin production and antioxidant defense
Vitamin D	Cholecalciferol	β-cell function	Enhances insulin secretion and sensitivity
Coenzyme Q10	Ubiquinone	Mitochondrial function	Improves cellular energy metabolism

Omega-3 fatty acids	EPA, DHA	Anti-inflammatory pathways	Reduces insulin resistance
Probiotics	Lactobacillus spp.	Gut microbiota	Improves insulin sensitivity and metabolic health
Green tea extract	EGCG	AMPK activation	Enhances glucose uptake
Gymnema sylvestre	Gymnemic acids	Glucose absorption	Reduces intestinal glucose absorption

Functional Foods and Nutraceutical Interaction

The therapeutic efficacy of functional foods and nutraceuticals in diabetes management is primarily attributed to their ability to act on multiple metabolic pathways simultaneously, thereby addressing the multifactorial nature of the disease. Unlike pharmacological agents that typically target a single biochemical pathway, these dietary interventions exert pleiotropic effects through a network of interconnected mechanisms.

One of the primary mechanisms involves the inhibition of carbohydrate-digesting enzymes such as α-amylase and α-glucosidase, which delays the breakdown of complex carbohydrates and reduces the rate of glucose absorption in the small intestine. This results in attenuation of postprandial hyperglycemia [15]. In parallel, several bioactive compounds activate AMP-activated protein kinase (AMPK), a central regulator of cellular energy homeostasis. Activation of AMPK enhances glucose uptake in skeletal muscle through GLUT4 translocation and suppresses hepatic gluconeogenesis, thereby contributing to improved glycemic control [4].

Antioxidant activity represents another critical mechanism, as oxidative stress plays a central role in the progression of insulin resistance and β-cell dysfunction. Bioactive compounds such as polyphenols and flavonoids neutralize reactive oxygen species and protect pancreatic β-cells from oxidative damage, preserving insulin secretion capacity [1]. Additionally, anti-inflammatory effects mediated through inhibition of transcription factors such as NF-κB reduce the production of pro-inflammatory cytokines, thereby improving insulin signaling.

Furthermore, modulation of gut microbiota has emerged as a key pathway through which functional foods exert metabolic benefits. Prebiotic fibers such as inulin promote the growth of beneficial microbial populations, leading to increased production of short-chain fatty acids.

These metabolites enhance insulin sensitivity, regulate appetite hormones, and reduce systemic inflammation [3]. The integration of these mechanisms highlights the superiority of functional foods and nutraceuticals as multi-target therapeutic strategies compared to conventional single-target pharmacological approaches [4].

Table 3: Bioactive Compounds and Molecular Mechanisms

Bioactive	**Source**	**Molecular Pathway**	**Detailed Mechanism**	**Outcome in Diabetes**
β-glucan	Oats, barley	GI viscosity, SCFA	Forms gel, delays glucose absorption; fermentation produces SCFAs	Reduced postprandial glucose spikes
Quercetin	Apples, onions	AMPK activation	Enhances GLUT4 translocation and glucose uptake	Improved insulin sensitivity
Curcumin	Turmeric	NF-κB inhibition	Reduces inflammation and oxidative stress	Improved insulin signaling
Resveratrol	Grapes	SIRT1/AMPK	Enhances mitochondrial function and energy metabolism	Improved glucose metabolism
Inulin	Chicory root	Gut microbiota	Promotes SCFA production and beneficial bacteria	Improved insulin sensitivity
Catechins (EGCG)	Green tea	AMPK activation	Increases glucose uptake and fat oxidation	Reduced insulin resistance
Anthocyanins	Berries	Antioxidant/AMPK	Improves endothelial and metabolic function	Better glycemic control
Berberine	Medicinal	AMPK	Reduces hepatic	Lower fasting

	plants		glucose production	glucose
Omega-3 fatty acids	Fish oil	Anti-inflammatory	Reduces cytokine production	Improved insulin resistance

Glycemic Index-Based Functional Food Selection

The glycemic index (GI) is a fundamental parameter in the dietary management of diabetes, as it reflects the rate at which carbohydrate-containing foods elevate blood glucose levels. Foods with a low GI are digested and absorbed more slowly, resulting in a gradual rise in blood glucose and reduced insulin demand. This controlled glycemic response is particularly beneficial in preventing postprandial hyperglycemia and improving long-term glycemic control [14].

In addition to GI, the presence of bioactive compounds further enhances the functional value of these foods. Low-GI foods rich in dietary fiber, resistant starch, and polyphenols not only regulate glucose release but also influence metabolic pathways such as insulin signaling and inflammation. Therefore, the combined consideration of glycemic index and bioactive composition provides a more comprehensive framework for selecting functional foods in diabetes management [15].

Table 4: Glycemic Index of Key Functional Foods

Food	GI	Category	Functional Role in Diabetes
Barley	28	Low GI	High β-glucan improves insulin sensitivity
Lentils	32	Low GI	Protein and fiber slow glucose release
Apple	36	Low GI	Polyphenols inhibit carbohydrate digestion
Orange	43	Low GI	Fiber and vitamin C reduce glycemic response
Sweet potato	44	Low GI	Resistant starch stabilizes glucose levels
Oats	55	Medium GI	β-glucan moderates glucose absorption
Brown rice	68	Medium GI	Better alternative to refined grains
White rice	73	High GI	Rapid glucose release, not ideal for diabetes

Potato (boiled)	78	High GI	Rapid digestion increases glucose spikes

Clinical Evidence and Quantitative Outcomes of Functional Foods and Nutraceuticals in Diabetes

The translational significance of functional foods and nutraceuticals in diabetes management is strongly supported by clinical evidence demonstrating measurable improvements in glycemic control and metabolic parameters. Unlike theoretical or mechanistic insights alone, human intervention studies provide quantifiable outcomes such as reductions in glycated hemoglobin (HbA1c), fasting blood glucose (FBG), postprandial glucose levels, and insulin resistance indices. These parameters are critical indicators of long-term glycemic regulation and risk reduction for diabetic complications [15].

Functional foods such as whole grains, millets, and legumes primarily exert their effects through modulation of postprandial glycemia and improvement in insulin sensitivity over time. Their benefits are generally gradual but sustained, owing to their influence on digestion kinetics, gut microbiota, and metabolic signaling pathways. In contrast, nutraceuticals, due to their concentrated bioactive composition, often demonstrate more pronounced and dose-dependent effects, particularly in reducing HbA1c and fasting glucose levels. Certain nutraceuticals, such as berberine and fenugreek, have shown efficacy comparable to conventional pharmacological agents in clinical settings [5][6].

The magnitude of these effects varies depending on dosage, duration of intervention, baseline metabolic status, and study design. However, consistent evidence indicates that even modest reductions in HbA1c (0.3–1.5%) are clinically meaningful and contribute significantly to reducing the risk of microvascular and macrovascular complications. The integration of these interventions into dietary strategies therefore provides a scientifically validated and practical approach to diabetes management [7][8][11].

Table 5: Clinical Outcomes of Functional Foods and Nutraceuticals in Diabetes

Functional Food / Nutraceutical	Dose (Clinical Range)	Duration	Outcome Parameter	Observed Clinical Effect	Reference

Oat β-glucan	3–5 g/day	4–12 weeks	HbA1c	↓ 0.3–0.6%	[15]
			Fasting blood glucose	↓ 10–15%	[15]
Barley β-glucan	3–6 g/day	6–12 weeks	HbA1c	↓ 0.4–0.7%	[15]
			Insulin sensitivity	↑ 15–25%	[14]
Millets (finger/foxtail)	50–100 g/day	8–16 weeks	HbA1c	↓ 0.5–1.0%	[5]
			Postprandial glucose	↓ 20–30%	[5]
Legumes (lentils, chickpeas)	50–100 g/day	6–12 weeks	HbA1c	↓ 0.3–0.5%	[6]
			Glycemic response	↓ 15–25%	[6]
Fenugreek	5–25 g/day	4–12 weeks	HbA1c	↓ 0.5–1.2%	[7]
			Fasting blood glucose	↓ 15–25%	[7]
Bitter gourd	2–3 g/day (extract)	4–12 weeks	Fasting blood glucose	↓ 10–20%	[7]
			Postprandial glucose	↓ 15–25%	[7]
Cinnamon	1–6 g/day	6–12 weeks	HbA1c	↓ 0.3–0.5%	[8]
			Fasting blood glucose	↓ 10–15%	[8]
Curcumin	500–1500 mg/day	8–12 weeks	HbA1c	↓ 0.5–0.8%	[9]

			Inflammatory markers	↓ 20–30%	[9]
Resveratrol	150–500 mg/day	8–12 weeks	Insulin sensitivity	↑ 20–30%	[10]
			HbA1c	↓ 0.3–0.6%	[10]
Berberine	500 mg (2–3 times/day)	12–16 weeks	HbA1c	↓ 0.8–1.5%	[11]
			Fasting blood glucose	↓ 20–30%	[11]
Probiotics	10^8–10^{10} CFU/day	6–12 weeks	HbA1c	↓ 0.3–0.5%	[12]
			Insulin resistance	↓ 10–20%	[12]
Green tea extract (EGCG)	300–800 mg/day	8–12 weeks	Fasting blood glucose	↓ 10–15%	[13]
			Body weight	↓ 2–4%	[13]

highly effective, are often associated with a range of adverse effects due to their potent and targeted pharmacological actions. In contrast, functional foods and nutraceuticals generally exhibit a more favorable safety profile, largely owing to their natural origin and multi-targeted mechanisms. However, they are not entirely devoid of side effects, especially when consumed in high doses or as concentrated extracts.

Metformin, the first-line drug for type 2 diabetes, is commonly associated with gastrointestinal disturbances such as nausea, diarrhea, abdominal discomfort, and, in rare cases, lactic acidosis, particularly in patients with renal impairment. Sulfonylureas, which stimulate insulin secretion, carry a significant risk of hypoglycemia and weight gain. Insulin therapy, while essential in advanced cases, is also linked to hypoglycemia, weight gain, and the risk of lipodystrophy at injection sites.

In comparison, nutraceuticals such as fenugreek, cinnamon, and berberine are generally well tolerated but may cause mild gastrointestinal discomfort, including bloating, diarrhea, or nausea, especially at higher doses. Berberine, despite its efficacy, can cause gastrointestinal upset and may interact with certain medications due to its effect on cytochrome P450 enzymes. Similarly, excessive intake of cinnamon may pose a risk of hepatotoxicity due to coumarin content, particularly in Cassia cinnamon varieties.

Functional foods, being part of the regular diet, are typically associated with minimal adverse effects and provide additional nutritional benefits. However, excessive consumption of high-fiber foods may lead to gastrointestinal discomfort, including flatulence and bloating. Probiotic supplementation, although beneficial for gut health, may cause mild digestive disturbances during initial use.

Overall, while pharmacological therapies offer rapid and significant glycemic control, they are often accompanied by dose-dependent side effects. In contrast, functional foods and nutraceuticals provide a safer and more sustainable approach with fewer and milder adverse effects, making them suitable for long-term management and preventive strategies. A balanced integration of both approaches can optimize therapeutic outcomes while minimizing risks [17].

Table 6: Side Effects Comparison of Antidiabetic Drugs and Nutraceuticals

Category	**Example**	**Common Side Effects**	**Severity**	**Additional Notes**
Biguanides	Metformin	Nausea, diarrhea, abdominal discomfort	Mild–Moderate	Rare risk of lactic acidosis
Sulfonylureas	Glibenclamide	Hypoglycemia, weight gain	Moderate–Severe	Requires careful dose monitoring
Insulin therapy	Insulin injections	Hypoglycemia, weight gain, lipodystrophy	Moderate–Severe	Risk increases with improper dosing
Thiazolidinediones	Pioglitazone	Weight gain, edema	Moderate	Risk of cardiovascular complications

Fenugreek	Seed powder	Bloating, diarrhea	Mild	Dose-dependent effects
Cinnamon	Powder/extract	Liver toxicity (high doses)	Mild–Moderate	Coumarin-related risk
Berberine	Alkaloid extract	GI discomfort, constipation	Mild–Moderate	Drug interaction potential
Curcumin	Supplement	Mild GI upset	Mild	Generally safe at recommended doses
Probiotics	Lactobacillus spp.	Gas, bloating (initial)	Mild	Temporary effects
High-fiber foods	Oats, legumes	Flatulence, bloating	Mild	Adaptation occurs over time

Conclusion

Functional foods and nutraceuticals represent a scientifically substantiated and mechanistically robust approach to diabetes management, offering benefits that extend beyond conventional nutritional support. Their ability to modulate multiple metabolic pathways—including glucose absorption, insulin signaling, oxidative stress, inflammation, and gut microbiota—positions them as effective adjuncts in the comprehensive management of diabetes. Unlike single-target pharmacological agents, these interventions operate through synergistic and pleiotropic mechanisms, thereby addressing the multifactorial nature of the disease. Clinical evidence demonstrates that both functional foods and nutraceuticals contribute to meaningful improvements in glycemic parameters, including reductions in HbA1c, fasting blood glucose, and insulin resistance. While their effects may be comparatively gradual, they are sustainable and accompanied by fewer adverse effects, making them particularly suitable for long-term management and preventive strategies. Nutraceuticals such as berberine and curcumin have shown efficacy approaching that of standard antidiabetic drugs, highlighting their potential as complementary therapeutic agents. However, despite their promising role, functional foods and nutraceuticals should not be considered replacements for pharmacotherapy in advanced or uncontrolled diabetes. Instead, their integration into dietary and clinical frameworks should be guided by evidence-based recommendations, individual patient needs, and careful consideration of dosage and interactions. Future research focusing on personalized nutrition, dose optimization, and large-scale clinical trials will further strengthen their application in clinical practice. In conclusion, the strategic incorporation of functional foods and nutraceuticals into diabetes management offers a holistic, safe, and sustainable approach that complements conventional therapies and contributes to improved metabolic health outcomes.

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From Farm to Glycemic Function: A Nutritional and Therapeutic Analysis of Ragi as a Functional Superfood for Diabetes Management and Metabolic Health

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Abstract

Ragi or Finger millet (Eleusine coracana L) occupies a unique position among the traditional cereals because of its agronomic resilience high mineral density and a grain matrix possessing fibre and polyphenols. To a large extent the characteristic features of Ragi are related to its production ecology. This chapter examines Ragi from farm to function. It covers the production ecology of Ragi, nutritional composition, processing behaviour, glycemic properties and actual dietary uses in diabetes and the metabolic syndrome. This analysis shows that when ragi is used in its whole state or minimally processed form as a cereal grain, it may be a diaetic-friendly food, especially when combined with adequate protein, vegetables, healthy fat and quantities. The chapter further assesses the extent to which soaking, germination, malting, fermentation, roasting, milling and composite-flour formulation modify antinutrient, mineral availability, starch digestibility, sensory quality, glycemic response. Research indicates that ragi (red/black

finger millet) consumption may help with postprandial glucose moderation, contribute to the feeling of fullness, ensure dietary diversity, and promote sustainable nutrition. However, the effects are not similar across products and/or people. Overly large portions, sugar-rich malted drinks and refined ragi snacks may lower its metabolic advantage. The chapter closes by stating that ragi can easily be added to medical nutrition therapy and public health nutrition as a culturally acceptable millet-based food that may be offered to patients but should not be used as a substitute for clinical care, blood glucose monitoring and individualized dietetic care.

Keywords

Ragi; finger millet; diabetes management; glycemic index; functional food; metabolic health; millet nutrition

1. Introduction

1.1 Diabetes as a Public Health Challenge

Diabetes today has moved from a clinical issue to a major public health problem. Furthermore, dietary quality, obesity, physical inactivity, urbanization and social determinants impact the risk for diabetes. According to the International Diabetes Federation, in 2024, an estimated 589 million adults i.e. aged 20–79 years are projected to have diabetes worldwide. Furthermore, IDF also states in their report that this number will rise substantially by 2050. According to the World Health Organization, the prevalence of diabetes among adults doubled between 1990 and 2022, and there remains a large treatment gap in low- and middle-income settings (World Health Organization [WHO], 2024). In 2021, the national ICMR study showed light on the situation of diabetes in the country. According to this study, nearly 101 million people suffer from diabetes apart from 136 million with prediabetes. Further, the study classified diabetes as a serious metabolic risk which is becoming common among both rural and urban people. This also indicates that diabetes is no longer limited to the affluent class people. (Anjana et al., 2023)

1.2 Dietary Quality and Whole-Grain Relevance

In light of this, dietary advice now focuses not just on carbohydrate quantity, but also quality, alongside food structure, fibre content, processing and meal context. The current diabetic’s diet should focus on foods with nutrient-dense carbohydrates, whole grains, legumes, vegetables, fruit and dietary fibre, while limiting refined grains and added sugars (ADA, 2025; ICMR-NIN, 2024). The scientific rationale for an increased focus on traditional cereals and millets will not be rooted in the identity of these grains as “miracle” foods but as foods imbedded in the culture offering benefits when used appropriately that can improve diet diversity and metabolic syndrome quality.

1.3 Functional Significance of Ragi

Ragi or finger millet is particularly relevant as it connects agricultural resilience with nutritional functionality. In India, it is eaten as ragi mudde, roti, dosa, idli, porridge, malted drinks and composite flour products. Its high calcium, fibrous seed coat, phenolic compounds and adaptability to semi-arid farming systems makes it a strong candidate for inclusion in diabetes-sensitive food systems (Devi et al. 2014; Rao et al. 2017). The phrase functional superfood is used here with caution. Ragi shouldn’t be seen as pharmacotherapy, but as food with structural and biochemical properties that have the potential to assist with glycaemic and metabolic management as part of an overall healthy dietary pattern.

2. Ragi from the Farm to the Food System

2.1 Agronomic Resilience and Production Ecology

Ragi is a cereal grain of the family of Poaceae, which is widely grown in some parts of South Asia and Africa. The stores have been recognized for their valuable agronomic qualities, such as drought tolerance, modest input requirements and suitability for marginal and rain-fed areas. According to Food and Agriculture Organization (FAO) (2023), in the International Year of Millets, millets are featured as crops that can grow on arid lands with minimum inputs and contribute to climate-resilient agriculture and food security and market opportunities for smallholders.

2.2 Millet Promotion and Food-System Diversification

Promoting millet, in the Indian context, is also a response to the need for affordable, locally adaptable, and nutritionally dense alternatives to reliance on refined cereals (ICMR-NIN 2024; Rao et al. 2017).

2.3 Translation from Production to Consumer Health Value

Ragi's farm-to-food-system value is its agronomic traits and nutritional traits reinforce each other. The adaptability of a crop whose growth does not suffer from moisture stress reduces the vulnerability of production while improvement of its grain quality may also help enhance diet quality of undernourished population affected by non-communicable disease. However, the benefits of the food system are realised only when whole or minimally refined ragi reaches consumers in acceptable, affordable and safe forms. Over-refining, adding excessive sugar, or branding ragi as a highly processed snack or food can disconnect the grain from its health benefits.

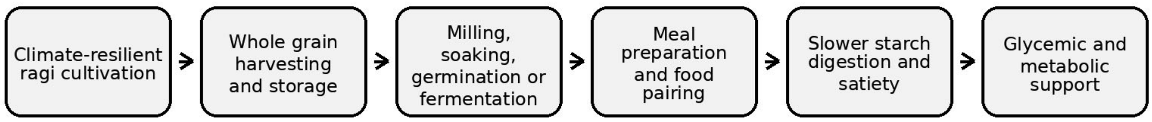

Figure 1. Farm-to-Glycemic Function Pathway of Ragi.

3. Nutritional Composition of Ragi

3.1 Whole-Grain Matrix and Mineral Density

Nutritionally, ragi is a carbohydrate-rich cereal, but its metabolic relevance cannot be inferred from carbohydrate content alone. Its whole-grain matrix contains protein, minerals, fibre fractions, phenolic compounds, phytates, and other phytochemicals, many of which are concentrated in the seed coat (Onipe & Ramashia, 2022). Indian food composition data consistently identify ragi as one of the most calcium-dense cereals, with commonly cited values around 344 mg calcium per 100 g raw grain, substantially higher than polished rice and wheat (Longvah et al., 2017; Rao et al., 2017). Its iron, phosphorus, potassium, magnesium, and amino acid profile further add to its role in diets where cereal staples dominate.

3.2 Comparative Nutritional Value Against Common Staples

Compared with polished rice, ragi provides a denser mineral and fibre matrix and is less dependent on refinement for culinary use. Compared with wheat, it has lower protein but a stronger calcium profile and the advantage of being naturally gluten-free. These comparisons should not be interpreted as a recommendation to replace all cereals with ragi. Rather, ragi can diversify cereal intake and reduce dependence on highly milled staples. In diabetes care, such diversification is valuable because repeated high-glycemic meals based on polished rice or refined wheat products can amplify postprandial glucose exposure, especially when meals lack vegetables, pulses, and protein.

3.3 Comparative Nutrient Profile

Table 1. Nutritional Profile of Ragi Compared with Common Staple Cereals

Nutrient or component	Ragi/finger millet	Polished rice	Wheat/whole wheat flour	Relevance for diabetes and metabolic health
Energy (kcal/100 g)	Approx. 328-336	Approx. 345	Approx. 341-346	Energy density is comparable; portion size remains essential.
Protein (g/100 g)	Approx. 7.3	Approx. 6.8	Approx. 11.8	Protein pairing is needed because cereal protein alone is not sufficient for diabetes meals.
Carbohydrate (g/100 g)	Approx. 72.0	Approx. 78.2	Approx. 69-71	Carbohydrate quality, food matrix, and meal pairing matter more than total carbohydrate alone.
Fat (g/100 g)	Approx. 1.3-1.5	Approx. 0.5	Approx. 1.5	Low fat content makes cooking method and added fat more relevant than grain fat.

Nutrient or component	Ragi/finger millet	Polished rice	Wheat/whole wheat flour	Relevance for diabetes and metabolic health
Fibre fraction	Higher than polished rice; values vary by analytical method	Low after polishing	Moderate to high in whole wheat	Fibre may support satiety, slower digestion, and gut fermentation.
Calcium (mg/100 g)	Approx. 344	Approx. 10	Approx. 30-48	Ragi is a notable cereal source of calcium, useful for diet diversity.
Iron (mg/100 g)	Approx. 3.9	Approx. 0.7	Approx. 3.5-4.9	Iron contribution is useful, but bioavailability may be affected by phytates and polyphenols.

Note. Values are approximate per 100 g raw edible portion and vary by cultivar, processing, and analytical method. Sources: Longvah et al. (2017), Rao et al. (2017), and Onipe and Ramashia (2022).

4. Bioactive Compounds and Functional Properties

4.1 Seed-Coat Phenolics and Dietary Fibre

The metabolic significance of ragi lies partly in the seed coat, where dietary fibre and polyphenols are concentrated. Finger millet contains phenolic acids, flavonoids, tannins, phytates, and antioxidant constituents that may influence carbohydrate digestion, oxidative stress, inflammatory tone, and lipid metabolism (Devi et al., 2014; Onipe & Ramashia, 2022). Seed coat phenolics extracted from finger millet have demonstrated inhibitory activity against alpha-glucosidase and pancreatic alpha-amylase in vitro, suggesting a plausible mechanism for moderating postprandial glucose absorption (Shobana et al., 2009).

4.2 Functional Mechanisms and Bio-availability Considerations

These mechanisms should be interpreted as supportive, not definitive. In vitro enzyme inhibition does not automatically translate into clinical glycemic control after a mixed meal. The bio-availability of phenolics, the degree of milling, the cooking matrix, and intestinal conditions all influence the final effect. Nevertheless, ragi's bio-active profile provides a biologically plausible rationale for studying it as a functional food within diabetes-sensitive diets. Polyphenols may reduce oxidative stress, fibre may enhance satiety and microbial fermentation, and phytate reduction through processing may improve mineral bio-availability (Wang et al., 2022).

4.3 Bioactive Components and Metabolic Roles

Table 2. Major Bio-active Components of Ragi and Their Possible Metabolic Functions

Bioactive component	Food source in ragi	Functional role	Diabetes/metabolic relevance	Supporting citation
Dietary fibre and resistant starch fractions	Whole grain, seed coat, fermented products	Increase viscosity, satiety, and colonic fermentation	May reduce rapid glucose appearance and support gut-derived metabolites	Mazhar et al., 2023; Onipe & Ramashia, 2022
Phenolic acids	Seed coat and bran-rich whole flour	Antioxidant activity and interaction with digestive enzymes	May help moderate oxidative stress and carbohydrate digestion	Devi et al., 2014; Shobana et al., 2009
Tannins	Outer seed coat	Protein and starch interaction; antioxidant activity	May lower starch digestibility, but excess can reduce mineral/protein availability	Chauhan & Sarita, 2018; Wang et al., 2022

Bioactive component	Food source in ragi	Functional role	Diabetes/metabolic relevance	Supporting citation
Phytates	Bran and aleurone fractions	Mineral binding; antioxidant role	Can reduce mineral bioavailability unless reduced by soaking, germination, or fermentation	Budhwar et al., 2020; Nkhata et al., 2018
Flavonoids	Seed coat and whole meal	Free-radical scavenging and enzyme modulation	May contribute to cardiometabolic protection within whole diets	Ofosu et al., 2020; Onipe & Ramashia, 2022
Calcium, magnesium, and trace minerals	Whole grain mineral matrix	Support mineral adequacy and metabolic enzyme systems	May improve diet quality, though not a direct glucose-lowering treatment	Longvah et al., 2017; Rao et al., 2017

5. Glycemic Function and Diabetes Management

5.1 Glycemic Index, Glycemic Load, and Meal Context

The original purpose of the glycemic index (GI) classification was to classify carbohydrate-containing foods according to their postprandial blood glucose response as compared to a reference food (Jenkins et al., 1981). The glycemic load (GL) takes into account both the amount of carbohydrate and the glycemic index. Thus is considered more practical for meals as compared to the GI. Within the context of diabetes management, postprandial glucose does not depend only on the grain itself the particle size, gelatinization, cooking time, fermentation, added sugar, fat, protein, fibre, acidity as well as meal sequence also matter (Brouns et al., 2005; Wolever et al., 1991).

5.2 Evidence from Millet-Based Dietary Studies

The encouraging millet evidence is heterogeneous. A systematic review and meta-analysis found that the glycemic index values of millet-based diets are lower than those of common control staples and that millet-based diets are associated with reductions in fasting and postprandial blood glucose in diabetic subjects (Anitha et al., 2021). A later meta-analysis that used difference-in-differences methods found significant reductions in fasting and postprandial blood glucose after regular millet consumption compared with major staple diets, while the evidence for HbA1c was less clear due to a lack of long-duration trials (Anitha et al., 2024). According to some studies on finger millet, certain finger millet preparations have shown lower glucose responses in comparison to rice-based meals or wheat-based meals, however, responses are different depending on the product type.

5.3 Clinical Dietetics and Product-Level Variation

For clinical dietetics, no ragi product can be assumed to be low-glycemic, and hence, safe. The response to a thick ragi mudde eaten along with sambar and vegetables may be different from a sweetened ragi malt or refined ragi biscuits. Whole flour, coarse particle size, intact bran, fermentation, protein pairing, and vegetable-rich accompaniments are more likely to sustain benefits. On the other hand, even the fact that a product contains millet will not be of much help if it is packaged food.

6. Processing Methods and Their Impact on Glycemic Response

6.1 Household Processing Techniques and Nutrient Availability

Processing determines if ragi behaves like a whole-grain staple or a quickly digestible refined product. Soaking, germination, malting and fermentation have been shown to lower the phytate and tannin concentration, improve the availability of mineral, increase the enzymatic activity and enrich sensory quality (Budhwar et al., 2020; Nkhata et al., 2018). Chauhan and Sarita (2018) examined the effect of germination and popping on antinutritional factors of finger millet. Moreover, they also noted the changes in mineral and protein values. Such changes may enhance nutrient availability; however, the glycemic impact is context dependent.

6.2 Industrial Processing, Particle Size, and Matrix Integrity

Cooking of starch to allow it to readily digest in the human intestines. The process of fine milling enlarging food surface area will increase starch digestibility. Also, fermentation will introduce organic acids and alter starch-protein-fibre interactions. Techniques like extrusion, flaking, and bakery formulation, which enhance convenience, can cause a loss of whole-grain integrity of products if formulated with refined flour, added sugars, and low-fibre ingredients

(Gowda et al., 2022; Wang et al., 2022). Thus, it is not whether ragi is used but how much whole grain remains and what is the final food matrix.

6.3 Processing Effects on Nutritional and Glycemic Properties

Table 3. Effect of Processing Methods on the Nutritional and Glycemic Properties of Ragi

Processing method	Nutritional effect	Possible glycemic effect	Advantages	Limitations	Citation
Soaking	Leaches some soluble antinutrients and hydrates grain	May modestly improve digestibility; effect depends on subsequent cooking	Simple household method	Nutrient losses may occur in discarded water	Nkhata et al., 2018
Germination/malting	Activates enzymes, reduces phytate, may improve vitamin and mineral availability	Can increase maltose and digestibility if over-malted; portion control needed	Improves bioavailability and flavour	Commercial malt drinks often contain sugar	Chauhan & Sarita, 2018; Budhwar et al., 2020

Processing method	Nutritional effect	Possible glycemic effect	Advantages	Limitations	Citation
Fermentation	Reduces antinutrients and may improve protein digestibility	Organic acids and microbial changes may moderate response in some foods	Useful for dosa/idli-type products	Final GI depends on batter ratio and cooking	Budhwar et al., 2020
Roasting/popping	Improves flavour and reduces some antinutrients	Heat may increase starch digestibility depending on product texture	Convenient and shelf-stable	Snack forms may promote overconsumption	Chauhan & Sarita, 2018
Fine milling or decortication	Improves texture but can reduce bran, fibre, and phenolics	May increase glycemic response due to smaller particle size	Improves acceptability in bakery applications	Loss of functional seed-coat components	Onipe & Ramashia, 2022; Gowda et al., 2022

Processing method	Nutritional effect	Possible glycemic effect	Advantages	Limitations	Citation
Extrusion/composite flours	Can create convenient foods and improve protein blends	Highly processed forms may raise digestibility and glycemic load	Product innovation and wider acceptance	Requires careful formulation without excess sugar/refined starch	Gowda et al., 2022; Wang et al., 2022

7. Therapeutic Relevance for Metabolic Health

7.1 Pathways for Glycemic, Satiety, and Diet-Quality Support

Ragi may support metabolic health through several pathways: improved cereal diversity, higher fibre intake than polished staples, bioactive phenolics, mineral density, and better satiety when prepared as a minimally processed food. In type 2 diabetes and prediabetes, replacing part of a refined cereal diet with whole or fermented ragi may help reduce postprandial glucose exposure and improve dietary quality (Anitha et al., 2021; Anitha et al., 2024). Its relevance may also extend to obesity and metabolic syndrome because higher-fibre grains can improve satiety and reduce energy intake when they displace refined, energy-dense foods.

7.2 Cardiometabolic and Inflammatory Considerations

Dyslipidemia and inflammation are also relevant because diabetes rarely occurs in isolation. Finger millet seed coat and whole grain constituents have been discussed in relation to antioxidant, hypocholesterolemic, and anti-inflammatory mechanisms, though much of this evidence is preclinical or based on intermediate outcomes (Devi et al., 2014; Onipe & Ramashia, 2022; Singh et al., 2022). A cautious interpretation is therefore necessary: ragi may contribute to a cardiometabolically favourable diet, but it should not be presented as a cure for diabetes, obesity, hypertension, or dyslipidemia. Therapeutic value comes from integration into a dietary pattern that includes vegetables, pulses, adequate protein, unsaturated fats, physical activity, medication adherence, sleep, and glucose monitoring.

7.3 Mechanistic Summary of Ragi and Metabolic Health

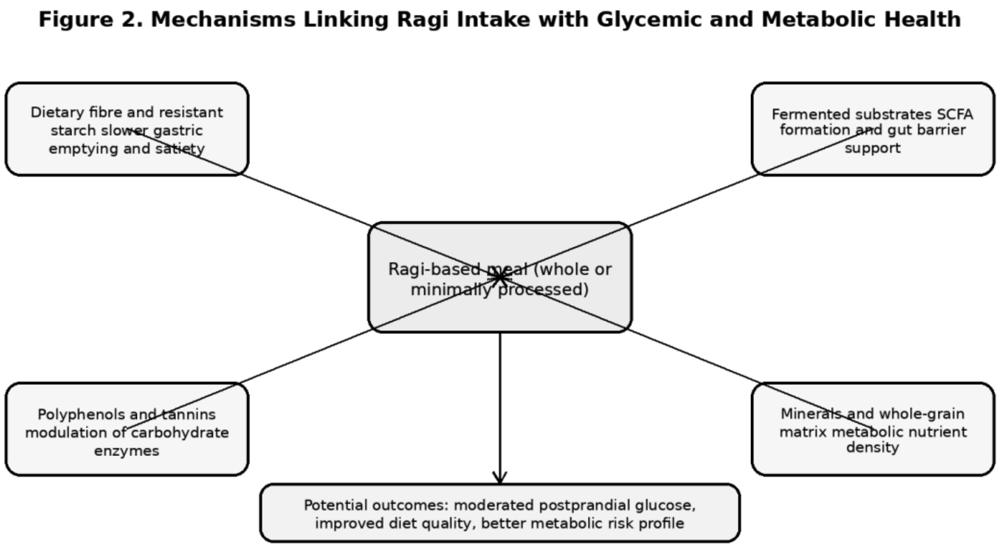

Figure 2. Mechanisms Linking Ragi Intake with Glycemic and Metabolic Health.

8. Ragi, Gut Microbiota, and Metabolic Regulation

8.1 Ragi Fibre, Resistant Starch, and Microbial Fermentation

Ragi's whole-grain matrix contributes insoluble fibre, resistant-starch fractions, and phenolic compounds that can reach the colon and interact with gut microbial metabolism. In diabetes-sensitive diets, this is relevant because microbial fermentation of complex carbohydrates produces short-chain fatty acids that are associated with appetite regulation, intestinal barrier support, inflammatory modulation, and glucose-insulin homeostasis (Mazhar et al., 2023; Singh et al., 2022).

8.2 Short-Chain Fatty Acids and Insulin Sensitivity

Short-chain fatty acids, particularly acetate, propionate, and butyrate, are increasingly discussed as mediators between high-fibre diets and metabolic regulation. Systematic evidence indicates that these metabolites may be associated with insulin sensitivity, although clinical effects vary with host microbiota, diet background, body composition, medication status, and intervention duration (Pham et al., 2024). Ragi should therefore be considered a dietary support for metabolic quality rather than an independent microbiome therapy.

8.3 Fermentation, Meal Structure, and Gut-Metabolic Outcomes

Traditional fermented preparations such as ragi dosa or idli may improve acceptability and alter the starch-protein-fibre matrix through microbial activity and organic-acid formation. These changes can support slower carbohydrate digestion and gut fermentation when the final meal is prepared without excess sugar or refined starch. However, the benefits depend on batter composition, portion size, accompaniments, and individual glucose monitoring.

9. Practical Dietary Applications and Plate Planning for Diabetes Care

9.1 Diabetes-Friendly Ragi-Based Food Applications

The clinical value of ragi is maximised when the grain is used in measured, unsweetened, whole-grain, or fermented forms. Table 4 translates this principle into common household applications by linking food preparation, glycemic considerations, practical dietary use, and cautions relevant to diabetes care.

Table 4. Diabetes-Friendly Ragi-Based Food Applications

Food preparation	Suggested dietary use	Glycemic consideration	Practical recommendation	Caution
Unsweetened ragi porridge	Breakfast or evening meal component	Liquid/semi-solid forms may be consumed quickly	Add curd, nuts, seeds, or dal-based side dish	Avoid sugar, jaggery, and sweetened mixes
Ragi roti	Lunch or dinner staple	Portion depends on flour quantity and meal context	Pair with dal, vegetables, curd, and salad	Do not add refined flour in large proportions
Ragi dosa/idli	Fermented breakfast option	Fermentation may improve acceptability; GI depends on batter ratio	Use with sambar and vegetable chutney	Limit potato fillings and sweet chutneys

Food preparation	Suggested dietary use	Glycemic consideration	Practical recommendation	Caution
Ragi mudde/ragi ball	Traditional staple meal	Dense carbohydrate portion can be large	Serve a measured portion with sambar/greens/protein	Avoid oversized servings
Ragi malt drink	Occasional meal component	Malted flour may be more digestible; sugar raises glycemic load	Use unsweetened, portion-controlled preparation	Commercial mixes may contain sugar
Composite ragi flour products	Roti, bread, noodles, or bakery formulations	Benefit depends on whole-grain proportion	Combine with pulses or high-fibre flours	Check labels for refined starch, sugar, and fat
Ragi snacks and biscuits	Occasional food only	Ultra-processed forms may lose whole-grain advantage	Prefer baked, high-fibre, low-sugar options	Millet label does not guarantee diabetes suitability

9.2 Plate Model and Portion Control

Portion planning is essential because ragi remains a carbohydrate-rich cereal even when it is nutrient-dense. A balanced plate model helps patients position ragi as one part of the meal rather than as an unrestricted therapeutic food, especially when medication, glucose monitoring, and individualized dietetic advice are part of care.

Figure 3. Diabetes-Friendly Ragi Plate Model

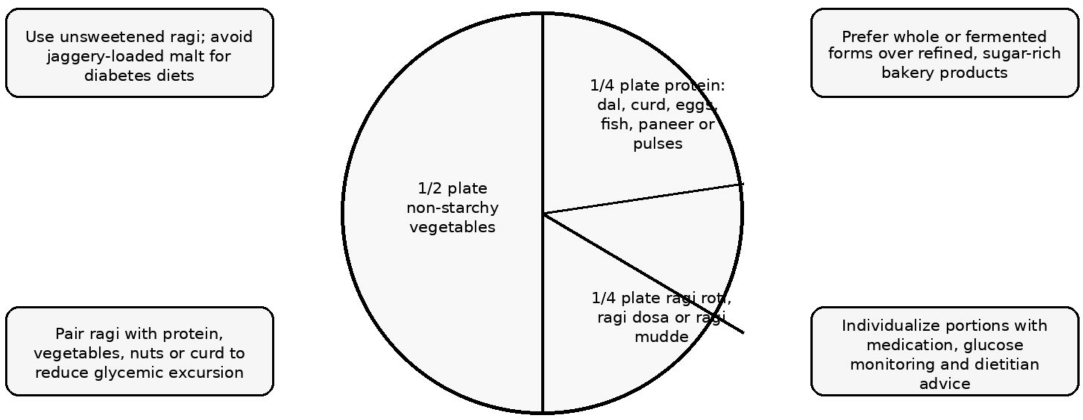

Figure 3. Diabetes-Friendly Ragi Plate Model.

10. Public Health and Community Nutrition Perspective

10.1 Community Nutrition and Diabetes Prevention

Ragi has public health relevance as prevention of diabetes cannot take place solely through clinic-based counseling. Affordable foods, culturally acceptable recipes, supply-chain support, and clear cooking instructions are essential for community nutrition. The recent endorsement of millet in India has generated fresh focus on traditional foods and nutrition-sensitive agriculture. According to serial organisation namely FAO millet initiative and Indian public communications millets are not only nutritious grains but are also resilient to adverse climatic conditions and have the potential to strengthen sustainable market opportunities (FAO 2023; Press Information Bureau 2024).

10.2 Public Education, Recipe Acceptability, and Local Food Practice

Ragi can provide calcium, fibre, and cereal diversification for school, community kitchen, women nutrition and elders care. In diabetes education, it can be used to teach the distinction between a whole food, which is an unprocessed food item, and a processed health claim, which is not a whole food. The message should not be 'eat unlimited ragi', but rather, 'use ragi wisely as part of a balanced plate' . Public health nutrition should also address acceptability; recipes must be tasty, cheap, simple and compatible with local meal patterns. Demonstrations in the community can show unsweetened ragi porridge, fermented ragi dosa, ragi roti with dal, mixed millet preparations with vegetables.

11. Constraints, Safety Considerations, and Research Gaps

11.1 Evidence Limitations and Product-Level Research Gaps

The evidence base on ragi and diabetes is encouraging but incomplete. The variation in glycemic response is first and foremost related to their product and particle size, cooking method, fermentation, sugar addition and portion sizes. Secondly, a number of millet studies include multiple millet types making the ragi-specific effects difficult to isolate. The literature on large randomized trials with standardized ration intervention regimens, continuous glucose monitoring, follow-up of HbA1c, microbiome analysis, lipids and long-term adherence measures is limited. Fourth, product-level research is required as commercial ragi foods are often quite different from the traditional whole-grain foods.

11.2 Safety, Suitability, and Individualized Dietary Caution

A nuanced approach is necessary for safety and suitability. Ragi has the presence of tannins and phytates which can reduce mineral bioavailability but soaking, germination and fermentation can reduce effects (Budhwar et al., 2020; Nkhata et al., 2018). Patients who are using insulin and/or insulin secretagogues should avoid making large changes to carbohydrate content without alerting their diabetes care team and making appropriate monitoring changes. This is because changes to meal glycemic load will alter the level of risk of hypoglycemia. Patients with chronic kidney disease, those with gastrointestinal intolerance and patients who are on highly individualized therapeutic diets must first be seen by a qualified clinician if there is an increase in millet consumption. Ragi is gluten-free; however, people with celiac disease or gluten sensitivity should be wary of cross-contamination or composite products containing it and wheat.

12. Conclusion

12.1 Farm-to-Function Synthesis

Understanding the value of ragi for diabetes and metabolic health necessitates a farm-to-function approach. At the farm level, it is a resilient millet well suited to diversified and climate-sensitive food systems. It provides a dense matrix of carbohydrates, fibre fractions, calcium, iron, magnesium, phenolics, tannins, and other bioactive compounds at the nutritional level. In its application in the kitchen, its health value will depend on whether it is used as a whole anti-microbial and fermented, slightly sweetened, portion-controlled food, or a refined version with added sugar. At the clinical level, part of a balanced meal plan for diabetes may help with postprandial blood glucose, satiety, diet variety and metabolic risk reduction.

12.2 Final Implications for Diabetes Care and Public Health Nutrition

Accordingly, the promotion of ragi should not be in the nature of a cure or as a total replacement for all cereals. Its best use as a functional millet within a larger dietary pattern rich in whole grains, pulses, vegetables, adequate protein, healthy fats, regular exercise, medication and personalized nutrition advice. When used appropriately ragi can complement diabetes-friendly dietary patterns and sustainable public health nutrition, but must not displace medical treatment or evidence-based clinical management.

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Pearl Millet: A Boon From Nature (From Traditional Field to Modern Plat)

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ABSTRACT

Pearl millet is an important nutritional cereal crop for people in the semiarid regions of Asia and Africa. Its potential to grow with minimal inputs in agriculture makes it a climate-friendly crop in the present scenario. As a climate-resilient crop, pearl millet can improve the economic and food security of farming families in arid regions while mitigating the adverse effects of climate change. Pearl millet's nutritional and therapeutic qualities are highlighted in this chapter. It is less dependent on artificial fertilizers and has good growth and productivity in low-nutrient soil. These characteristics make it the most widely grown crop in dry and semi-dry regions in parts of the world. Some research indicates that the frequent consumption of pearl millet may provide preventive effects against chronic diseases such as diabetes, cardiovascular disorders, psychiatric disorders, obesity, and malnutrition etc. Due to the presence of macro and micro nutrients in the grain. To raise awareness of pearl millet and make it a regular part of our daily diet and a potent option for sustainable food security, this chapter discusses its key features.

Keywords: economic and food security, nutritional and therapeutic qualities, artificial fertilizers, chronic diseases, sustainable food security

BACKGROUND

A healthy diet is essential for preventing malnutrition and many other chronic diseases. However, due to a changing ecosystem and an increasing population, there is now an imbalance between the demand and supply of nutritious food. Now is the time to turn back to our ancient traditional food millets. Despite their high nutritional value and potential as a prime source of food, millets are often disregarded owing to a lack of awareness (Thakur and Modi 2020). However, current research on millets has shown beneficial effects not only on human health but also on farmers' economic condition, agriculture, and future food security, which has raised interest in the field of study, including millets cultivation and consumption.

While all millets offer immense health benefits, pearl millet stands out as a nutritional powerhouse with superior nutrient density, climate resilience, and sustainability, and provides future food security more than other millets and cereal crops. All these qualities of pearl millet, make it distinct from other cereals, including coarse grains, too. That's why, in addition, pearl millet is called a super-food.

PRELUDE OF PEARL MILLET:

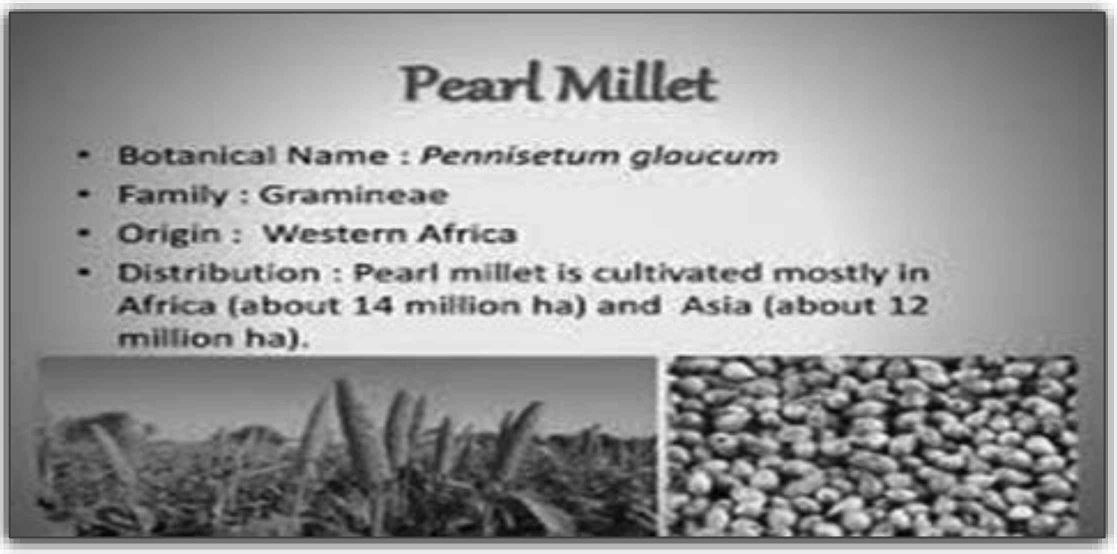

Figure 1 *(Source: https://www.slideshare.net/slideshow/pearl-millet-65423847/65423847)*

Pearl millet (Pennisetum glaucum), commonly called Bajra (Kumar et al. 2022), grown primarily in Asian and African countries for food and fodder, is an underutilized coarse-grain crop (Krishna and Meera, 2017). India has successfully grown pearl millet on 30 million hectares in the dry and semi-arid tropical region of Asia and Africa (Nembiar et al. 2011), providing a staple meal for 90 million impoverished people. It accounts for over half of millet production worldwide. Approximately 95% of the total population lives in developing nations, with India ranking first in pearl production (Prashant et al., 2021).

ORIGIN OF PEARL MILLET:

It is estimated that pearl millet (Pennisetum glaucum (L.) R. Br. Poaceae) was domesticated between 3,000 and 5,000 years ago on the southern edge of the Sahara in Africa. From there, it moved to southern Asia. According to Andrews et al. (1993), pearl millet has undergone domestication, classification, biology, and adaptability. Stegmeier et al. (1990), Adeola et al. (1996), and Andrews et al. (1996) have all assessed the significance and potential of pearl millet as a grain crop, as well as its development and potential in the United States.

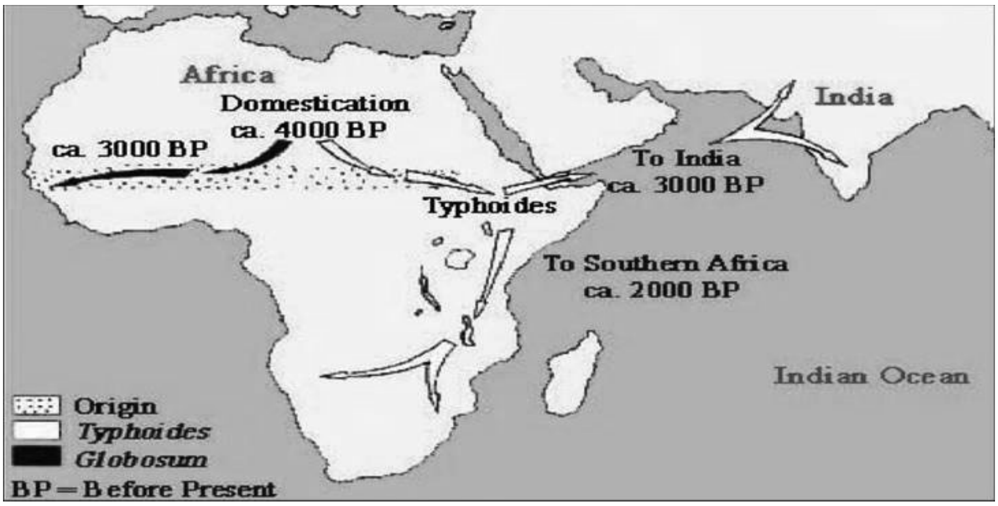

Figure 2 *(Source: Bhattacharjee et al. 2007 https://www.researchgate.net/figure/Origin-of-pearl-millet_fig5_277128083)*

In the US, pearl millet has long been used for cattle grazing and feed production. It is farmed on more than 26 million hectares as a multipurpose cereal grain crop, mostly in arid and semi-arid regions of Africa and India, for food, feed, fodder, fuel, and mulch (FAO 2000). About 90 million people who live in semi-arid tropical regions of Africa and the Indian subcontinent rely on it as a staple crop (Gulia et al. 2007). Additionally, in the present time, pearl millet is enormously cultivated in five continents, i.e., Africa, Asia, North America, South America, and Australia for feed and food (Meena et al. 2024).

PRODUCTION AND CULTIVATION:

Pearl millet is the sixth most significant cereal crop after wheat, rice, corn, barley, and sorghum. It accounts for over half of the world's millet production and is extensively produced on 30 million hectares in the dry and semi-arid tropical regions of Asia and Africa (Satyvathi et al. 2021). India is the fourth-largest producer of pearl millet in the world, with an average production of 6.83 million tonnes and productivity of 1488 kg/ha in 2024-25. Pearl millet occupies 6.83 million hectares (2nd advanced estimate of 2024-25, Department of Agriculture & Farmer Welfare, India). More than 90% of the nation's pearl millet acreage is farmed in the major pearl millet growing states of Rajasthan, Maharashtra, Gujarat, Uttar Pradesh, and Haryana. Pearl millet is typically grown during the rainy season (Kharif), which runs from June to October. Additionally, it is grown on a modest scale in Gujarat and Maharashtra during the post-rainy (Rabi) season (November- February) and in parts of Gujarat, Rajasthan, and Uttar Pradesh during the summer (February- May) (ICAR-AICRP). Nearly 10% of India's rely on pearl millet as a staple diet, and about 85% of the crop is used for food (Singh 2025).

State wise Pearl Millet Production (Lakh-Tonnes) in India

Sr. No.	State	2021-2022	2022-2023	2023-2024
1	Rajasthan	37.40	51.05	42.81
2	Uttar Pradesh	19.51	20.46	21.95
3	Haryana	11.20	12.00	11.69
4	Gujarat	10.90	12.94	3.63
5	Madhya Pradesh	8.69	9.43	9.58
6	Maharashtra	6.19	4.68	2.01
7	Karnataka	1.71	1.77	1.56
8	Tamil Nadu	1.46	1.13	1.19
9	Andhra Pradesh	0.55	0.51	0.54
10	Jammu And Kashmir	0.05	0.10	0.00

*(**Source:** https://apeda.gov.in/milletportal/Pearl_millet.html)*

NUTRITIONAL VALUE:

The world's expanding population, which primarily relies on a diet low in micronutrients from cereal, faces a significant issue in the form of nutritional insecurity. Pearl millet serves as the primary energy source in conflict-prone regions of Asia and Africa, as well as parched tropics, after major energy cereal sources such as wheat, rice, and maize (APEDA: https://apeda.gov.in/milletportal). This is because pearl millet is nutritionally superior grain that is enriched with high amount of essential amino acids, carbohydrates, better fat digestibility, vitamins, and minerals (Goswami et al. 2020). A noteworthy characteristic of pearl millet is its high content of iron and zinc that can both raise hemoglobin levels and prevent conditions brought on by iron and zinc deficiencies (Chaudhary et al. 2023).

Pearl millet has a remarkable high nutritional value for a grain. It is rich in protein (13.4-18.6%), heavy in carbohydrate (67.5-76%), and low in cholesterol (5.6-7.8%), and high in polyunsaturated fat. It is also a great source of B vitamins (B1, B2, B6, and B12).

Table 1: *Nutritional value of Pearl Millet per 100g.*

Sr. No.	Parameters	Unit	Amount
1.	Energy	Kcal	360
2.	Protein	gm	12
3.	Fat	gm	5
4.	Carbohydrates	gm	67
5.	Fiber	gm	1
6.	Calcium	mg	42
7.	Phosphorous	mg	242
8.	Iron	mg	8

*(**Source:** Porwal et al. (2023). https://doi.org./10:30574/ijsa.2023.10.1.0828)*

Additionally, pearl millet is also rich in antioxidants, particularly phenolic compounds such as ferulic and coumaric acids. It has a sufficient amount of omega-3 fatty acids compared to any other cereal grain, which may help prevent and treat diseases such as diabetes, heart disease, arthritis, and certain cancers (Nambiar et al 2011).

Pearl millet is the only grain that maintains its alkaline qualities after cooking because it is gluten-free, which is protective for those people who are allergic to gluten, such as those with celiac disease (Khairwal et al. 2007).

KEY PROPERTIES OF PEARL MILLET:

Benefits of Pearl Millet

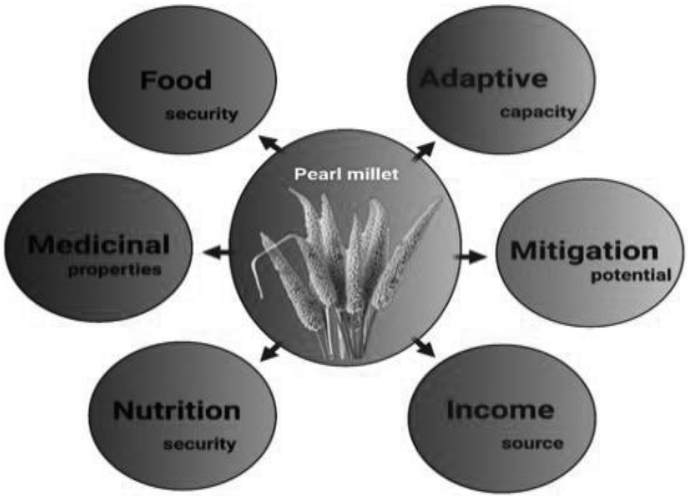

Figure 3(*Source: https://link.springer.com/chapter/10.1007/978-981-95-1256-0_8)*

Good for Planet: Crop production is impacted by climate change since it directly affects biophysical elements like animal and plant growth, as well as several sectors involved in food distribution and processing. To anticipate and modify farming to more efficiently maximize agricultural production, assessing the effect of global climate change on agriculture can be useful (Satayavathi et al. 2021). In contrast to other crops like rice, wheat, and maize, pearl millet can grow at extremely high temperatures with little water, and pearl millet also has the ability to grow rapidly in response to a brief period of favourable weather. It has one of the fastest growth rates among cereals under optimal conditions. When compared to other cereals, it also offers appropriate physical traits, such as resistance to drought, low soil fertility, and high salinity (Rai et al. 2008). The structural composition of pearl millet is 75% endosperm, 17% germ, and 8% bran, which make up this grain and are responsible for making it more nutritious than other cereals (Satankar et al. 2020). One reason for the enhanced nutritional content of pearl millet grain is that its germ fraction is roughly double that of sorghum (Andrew and Kumar 1991).

Good for Health: High levels of iron and zinc found in pearl millet may aid in raising hemoglobin levels. However, non-nutrient components, including polyphenols, phytate, and tannin, may reduce iron's bioavailability. Because of its high fibre content, pearl millet can aid with obesity and constipation. Additionally, pearl millet contains abundant antioxidants, including phenolic compounds, which may have anti-cancer properties (Sukar et al. 2020). When it comes to wheat allergies, pearl millet is the only grain that is gluten-free and restores its alkaline quality after cooking.

Pearl millet is recommended for treating peptic ulcers because it also helps reduce excess acidity. However, because of its high phosphorus levels, it also plays a part in bone growth and repair, and its high magnesium content lessens the severity of respiratory conditions like asthma (Sukar et al. 2020). The unresolvable fibres in pearl millet lessen the overindulgence bill of the human body that leads to gallstones (Malik 2015).

Another health concern linked to the present scenario is that a fussy and stressful lifestyle is associated with mental health disorders. To improve mental health with a sophisticated lifestyle, it's essential to have a balanced diet and obtain enough nutrients for mental wellness, such as antioxidants, folic acid, vitamin B6 and B12, and omega-3fatty acids as instructed by ICMR

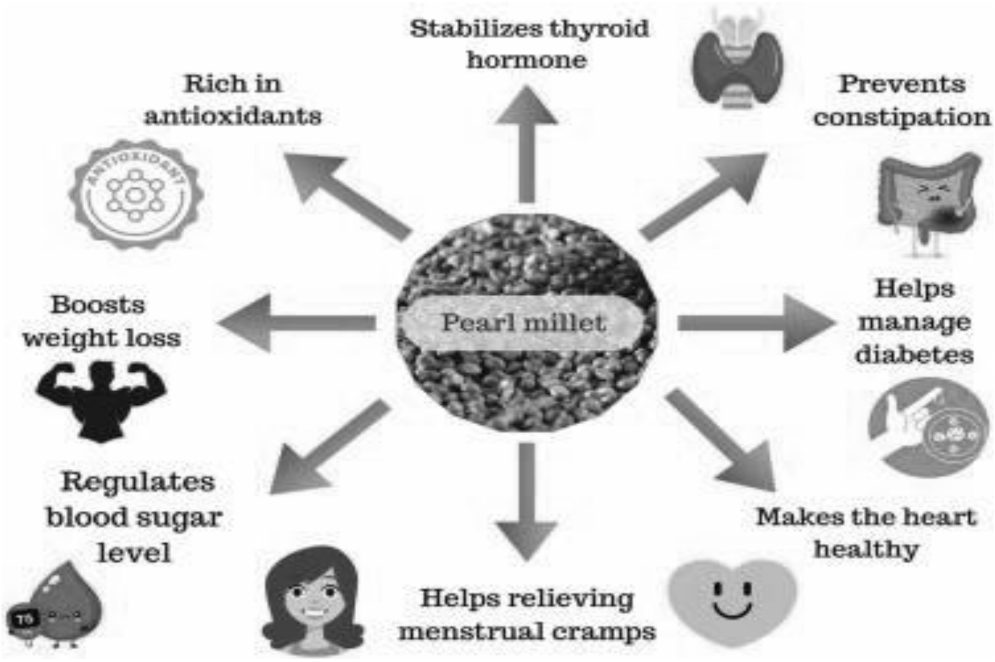

Figure 4

(Source: https://www.sciencedirect.com/science/article/abs/pii/S2949824424001095)

(Lim et al. 2016). All these nutrients that are essential for mental wellness are found together in pearl millet.

Good for Farmer: 600 million people in India rely on agriculture, and of them, small farmers own up to 2 hectares of land. Two-thirds of the net-sown area is rain-fed. Approximately two-thirds of this land is prone to drought, and about 40 million hectares are prone to flooding.

Geographically, the poorest farmers are usually in more vulnerable or peripheral areas, including floodplains or nutrient-deficient soils. The impoverished are also less equipped to respond and have very little capacity to deal with the effects of climate change and adjust to a shifting hazard burden because they have fewer financial and human resources (Tiwari et al. 2022). Pearl millet has the potential to subsist with these unpredictable climate responses due to its climate-resilient properties. It confers excellent results with minimal agricultural inputs, and its growing time period is also very short, hence farmers can get more yield in less time. Additionally, pearl millet is a nutrient-dense super food, it is proffers two-dimensional support to farmers. In another way, pearl millet is also useful for livestock, which provides better financial support for farming families. Because pearl millet crops require fewer resources and are adjusted to a changing climate, it is essential to seek other solutions (Daduwal et al. 2024)

Figure 5 *(Source: https://mel.cgiar.org/projects/-15/107/impact-of-icrisat-pearl-millet)*

ROLE OF PEARL MILLET IN DIABETES MELLITUS:

Diabetes mellitus, commonly referred to as diabetes, is a collection of metabolic conditions marked by persistently elevated blood sugar levels (Mechachate et al. 2021). In other words, it is called hyperglycemia, brought on by either a relative or absolute lack of insulin. The prevalence of diabetes is expected to increase from 2.8% in 2000 to 4.4% in 2030 worldwide. It’s possible that by 2030, there will be more than 366 million people with diabetes (Wild et al. 2004).

Pearl millet has several promising characteristics that support its potential importance in the treatment of diabetes mellitus. Due to its low GI, high fibre content, and phytochemical profile, pearl millet helps to control blood sugar levels. These qualities highlight pearl millet’s appropriateness as a healthy food option for anyone looking to successfully manage their blood sugar levels (Salar et al. 2017).

One of the main reasons pearl millet can help with glycemic management is its low glycemic index. Low GI foods are absorbed and digested more slowly, which causes blood sugar levels to rise gradually rather than sharply (Alzahrani et al. 2022). Pearl millet's high fibre content promotes a feeling of fullness and satiety, which can help control weight and lower total caloric consumption. Maintaining a healthy weight is essential for controlling Type 2 diabetes because it can improve insulin sensitivity and lower the risk of complications from the disease. Additionally, dietary fibre has been demonstrated to increase insulin sensitivity by affecting the secretion and efficiency of insulin, the hormone that controls blood glucose level (Singh et al. 2023). Therefore, adding pearl millet to meals can help stabilize blood sugar levels postprandially, or after meals, which is crucial for diabetics to maintain ideal glycemic control.

CONCLUSION:

Pearl millet has nutritional benefits and climate-resilience properties, making it an essential part of sustainable agriculture. Pearl millet thrives in arid regions with minimal water, making it ideal for regions with erratic patterns. It is more feasible for sustainable agriculture due to their shorter growth seasons and reduced input requirements. By incorporating pearl millet into agricultural operations, food security and environmental sustainability improved. It has the potential to completely transform agricultural landscapes everywhere around the world. In line with current health concerns, pearl millet's many functional qualities highlight its low glycemic index, which plays a great role in weight management and its ability to reduce the risk of chronic diseases such as diabetes, cardiovascular disorders, and obesity. Along with the presence of micronutrients in this grain helps to fight every type of malnutrition and hidden hunger. Therefore, it becomes essential for the government and researchers to promote pearl millet for consumption and cultivation among people and farmers, respectively.

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Millets In Traditional Indian Diets: Nutritional Benefits and Value Addition

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INTRODUCTION

A variety of small-seeded grasses known as millets are commonly cultivated as cereal grains for use as fodder and human nourishment all over the world. They belong to a functional or agronomic group rather than a taxonomic one. In the semi-arid tropical regions of Asia and Africa, particularly in India and Nigeria, millets are significant crops. 97% of the world's millet is produced in developing nations. The crop benefits from a short growth season under dry, hot circumstances, as well as from its production. The millet that is most frequently cultivated is pearl millet, a significant crop in Africa and parts of India. Despite being native to various regions of the world, millets are thought to have evolved in tropical western Africa because it is where they are most commonly seen now. Throughout human history, millets have played a significant role as a staple meal, particularly in Asia and Africa. For the past 10,000 years, East Asia has been cultivating them.

DISTRIBUTION OF MILLETS IN INDIA

For the years 2000 and 2009, India produced the most millets, followed by Nigeria. Eight types of millets are commonly grown in India under rain-fed conditions: sorghum, pearl millet, finger millet, foxtail millet, kodo millet, proso millet, barnyard millet, and little millet. Additionally, at least 4 to 5 types of millet are grown in each of the millet-growing regions, either as the main crop or as a supplementary crop with pulses, oilseeds, spices, and condiments. For instance, while sorghum and pearl millet are primary crops and allied crops, respectively, in Rajasthan's dry regions, the situation is the complete reverse in Gujarat and Rajasthan's eastern regions. Similar to Telangana, Andhra Pradesh, Maharashtra, and a portion of Central Asia, sorghum is planted as a major crop.

Similarly, the finger millet is a major crop in Gujarat and Tamil Nadu, but only a minor crop in Telangana. Millets' spatial distribution therefore greatly depends on the region's growing environment and rainfall levels, whether they are grown as a primary crop or as associated crops. While pearl millet rivals sorghum where yearly rainfall is less than 350 mm, sorghum predominates where annual rainfall exceeds 400 mm. Additionally, the majority of the southern and central states in India are home to small millets like finger millet, foxtail millet, barnyard millet, little millet, and proso millet, especially wherever the annual rainfall is below 350 mm. It's possible that no other cereal crop can thrive in these conditions of moisture stress.

However, despite having a wide range of environmental tolerance and abundant inter- and intra-species diversity, the cultivation of different millet species and variants has been steadily declining in the recent past. In a way, the millet-growing region is continuing to contract due to institutional support for millet crops being lacking in comparison to institutional promotion of rice and wheat. Despite this, many communities in the dry/rain fed regions continue to include a variety of millets in the traditional cropping patterns, which recognize millet as an essential part of the millet diet. These communities have understood the food benefits of millets for decades.

SORGHUM:

Warm-season crops like sorghum (*Sorghum bicolor* (L.) Moench) are not tolerant of low temperatures but are generally resistant to harmful pests and diseases. It goes by a number of names (such as great millet and guinea corn in West Africa, Asia and parts of Middle East). Animal feed is the primary use for the majority of the sorghum produced in North and Central America, South America, and Oceania. The grain is made up of a pericarp, endosperm, and germ, which are called naked caryopsis. Sorghums are divided into four classes despite their enormous physical diversity: grain sorghum, forage sorghum glum, grass sorghum, and Sudan sorghums and broomcorn. Following traits are used to classify sorghums.

- The pericarp's colour (white, yellow or red)
- The presence or absence of testicular pigmentation (tannins or not) thickness of the pericarp

- Endosperm hue (white, hetero yellow or yellow)
- Type of endosperm (normal, hetero waxy or waxy)

HEALTH BENEFITS OF SORGHUM

Obesity

In India, obesity is a growing issue and is positively correlated with a number of chronic illnesses, such as diabetes and cardiovascular disease (CVD). The prevalence of obesity appears to be reduced by consumption of high dietary fibre, according to empirical findings. Foods high in dietary fibre enhance the function of the large intestine and slow down the digestion and absorption process, lowering the risk of developing chronic diseases. Sorghum has special chemical and physical properties (bulk to the diet, viscosity, water holding and absorption capacity), which control the ensuing physiological behaviour. It is also high in dietary fibre. It contributes to hunger satisfaction, heightens satiety, and lowers risk factors for obesity.

Diabetes

Diabetes Mellitus is a complex metabolic condition that is a serious global health issue. Worldwide, the prevalence of type 2 diabetes is increasing at an alarming rate, particularly in India, where the prevalence of diabetes has risen to 14.3%. Measures to encourage a good eating pattern and lifestyle, including a balanced diet and physical activity, are necessary to prevent type 2 diabetes. People who eat three or more servings of whole grains in a day, especially from high-fiber cereals, are less likely to develop insulin resistance and the metabolic syndrome, common precursors of both T2D and Coronary Heart Disease (CHD). Whole grain-based diets typically lower triglycerides, blood pressure, and LDL cholesterol while elevating HDL cholesterol (Anderson, 2003). Sorghum has a high dietary fibre content and a low glycemic index, which may help Indians prevent and manage T2D. Foods that are rich in fibre, magnesium, vitamin E, phenolic compounds, and tannins minimize the risk of developing diabetes by delaying the abrupt rise in blood sugar and insulin levels.

In 2010, the National Institute of Nutrition (ICMR) and the Indian Institute of Millets Research, Hyderabad, collaborated on the National Agricultural Innovation Project to examine the Glycemic Index (GI) of foods based on sorghum (NAIP). The findings showed that diets made from sorghum have a low GI, which lowers postprandial blood glucose levels and glycosylated haemoglobin. Another study shows that non-obese patients with non-insulin-dependent diabetes mellitus (NIDDM) who drank sorghum bran papadi had significantly lower blood glucose levels. Boiling Yellow Jowar flour (coarse) had a lower glycemic index than flour made from the same kind, according to studies on the processing and cooking of white and yellow jowar varieties. The glycemic index of chapatti made from white Jowar flour was lower than that of yellow jowar flour in a similar manner. These changes in glycemic index due to processing and cooking play an important rolein diets followed in dietary management of diabetes.

Coronary Heart Disease

According to empirical data, eating whole grains regularly lowers the incidence of CVD. The risk of CVD and overall mortality is reduced by regularly consuming a balanced diet that contains whole grains, vegetables, fruit, fish, and chicken. In 2004, researchers from Harvard University discovered that consuming 40 grammes of whole grains per day lowers the risk of CHD by 20%. The study involved 27,000 males between the ages of 40 and 75.

Cancer

Studies conducted *in vitro* and *in vivo*method which demonstrated the protective effects of sorghum consumption against cancer. Sorghum contains polyphenols and tannins that have favourable melanogenic activity, anti-mutagenic and anti-carcinogenic qualities, and can act against human melanoma cells. According to Parbhoo et al. (1995), procyanidin extracts may stimulate cytochrome P-450, a protein that can transform some promutagens into derivatives that are mutagenic. The authors looked at 21 localities in each nation over the course of six years, and they discovered that sorghum consumption was associated with reduced oesophageal cancer mortality than wheat and corn. Conclusion: Sorghum's anti-carcinogenic components reduced the incidence of oesophageal cancer.

Oxidative Stress

Consuming sorghum has been shown to offer anti-cancer benefits in both in vitro and in vivo studies. Sorghum includes polyphenols and tannins that can inhibit human melanoma cells as well as have favourable melanogenic activity, anti-mutagenic, and anti-carcinogenic properties. Procyanidin extracts may induce cytochrome P-450, a protein that can change some promutagens into derivatives that are mutagenic, according to Parbhoo et al. (1995). The scientists found that sorghum consumption was associated with lower oesophageal cancer mortality than wheat and corn after examining 21 localities in each country over the course of six years. The anti-carcinogenic properties of sorghum decreased the incidence of oesophageal cancer.

Finger Millet

Eleusine coracana (L.) Gaertn, sometimes known as finger millet, is a cereal grass primarily produced for its grain. Up to 170 cm high, finger millet is a hardy, tufted, tillering annual grass. The name "finger millet" comes from the inflorescence, which is a panicle with 4–19 finger-like spikes that resemble a fist when ripe. Up to 70 alternating spikelets, each containing 4 to 7 tiny seeds, are produced by the spikes. The seed pericarp can be easily separated from the seed coat and is independent of the kernel. The staple grain of many African and South Asian nations is finger millet. Due to its ease of storage throughout years of famine, it is also regarded as a useful famine crop. The grain can be cooked like rice, processed to make porridge or flour, or used to make cakes. It is easily digestible, very nourishing, and flexible. Grain that has been sprouted is advised for newborns and the elderly. In Ethiopia, finger millet is also used to manufacture beer and arake, both of which produce byproducts that are fed to cattle. Although finger millet is predominantly utilised as a food grain, it is not frequently used for livestock since it is of lower quality for animals than maize, sorghum, and pearl millet. It is occasionally used in India to feed young calves, growing animals, ill, and recuperating animals.

Health benefits: Finger millet for losing weight:

Ragi contains an amino acid called Tryptophan which lowers appetiteand helps in keeping weight in control. Ragi gets digested at a slower rate thus keeps one away from intake ofexcessive calories. Also, fibres present in ragi give a feeling of fullness thus controls excessive food consumption.

Finger millet for bone health:

Calcium, which helps to strengthen bones, is abundant in ragi. It is a great natural calcium source for growing youngsters and older folks. Consuming ragi supports bone health in adults as well as bone development in developing children. Ragi can lower fracture risk and protect against diseases like osteoporosis.

Finger millet for diabetes:

The phytochemicals in finger millet aid in slowing down the digestive process. This aids in the management of diabetes-related blood sugar levels. A 2000 study indicated that eating a diet heavy in finger millet—which has more fibre than rice and wheat—can aid diabetics.

Additionally, the study discovered that a diet consisting primarily of whole finger millet has a decreased glycemic response, or a capacity to raise blood sugar levels. This is because of ragi flour contains ingredients that reduce the digestion and absorption of starch.

Finger millet for lowering blood cholesterol:

Lecithin and methionine, two amino acids found in finger millet, assist in lowering cholesterol levels by removing extra liver fat. Additionally, finger millet includes the amino acid threonine, which prevents liver fat from forming and lowers blood cholesterol levels.

Finger millet for anaemia:

Natural iron can be found in abundance in ragi. Consuming ragi aids the anaemia problem.

Finger Millet for Protein/ Amino Acids:

Ragi is a rich source of amino acids, which are necessary for both body repair and regular bodily function. Tryptophan, Threonine, Valine, Isoleucine, and Methionine are all amino acids found in finger millet. Isoleucine promotes skin health, aids in muscle recovery, and contributes to the creation of blood and bones. Valine is a necessary amino acid that promotes metabolism, aids in muscle coordination, and aids in tissue repair. It supports the body's nitrogen balance. Methionine is another essential amino acid that isn't present in most cereals but is nonetheless important for a number of bodily functions, aids in the removal of fat from the body, and serves as the body's primary source of sulphur. The body's natural antioxidant, glutathione, is produced with the help of sulphur.

Finger Millet for other health conditions:

Regular use of ragi may prevent undernourishment, degenerative illnesses, and early ageing. For high blood pressure, liver problems, asthma, and weak hearts, green ragi is advised. When a mother is nursing and her milk supply is low, green ragi is also advised.

Ragi is a very nourishing cereal that is great for keeping one's health in check. However, a high consumption could result in more oxalic acid being produced in the body. As a result, patients with kidney stones are not encouraged to do so (Urinary Calculi). Ragi can be consumed in a variety of ways and dishes. Among the most well-known Ragi delicacies are Ragi Roti, Ragi Dosa, Ragi Porridge, Ragi Upma, Ragi Cakes, and Ragi Biscuits.

Pearl Millet

Pennisetum glaucum (L.) R. Br., sometimes known as pearl millet, is a cereal grain that originated in Central tropical Africa and is now widely grown in India and the drier tropics. It was introduced into the Western state in the 1850s and spread to the Southeast and Gulf Coast states as a minor forage. Around 4000 to 5000 years ago, in the southern edges of the Central Saharan highlands, the plant was probably domesticated as a food crop. Since then, it has spread rapidly over the semi-arid tropics of Africa and Asia. A significant grain, fodder, and stover crop historically, pearl millet is largely grown in dry and subtropical regions of many developing nations. Production limitations arise as pearl millet growing spreads into unconventional places in arid and developed nations. Production limitations brought on by illnesses are becoming more significant as pearl millet agriculture spreads into previously untapped regions in temperate and affluent nations. The growth in interest in pearl millet as a potential crop in out-of-the-way places has not kept up with the dissemination of reliable information on crop diseases. The growing conditions of drought, poor soil fertility, and high temperatures are ideal for pearl millet. It works effectively in soils with low pH or excessive salinity. It can be grown in regions where other cereal crops, such maize or wheat, would not thrive because of its tolerance to challenging growth circumstances.

Health benefits:

Pearl millet provides various health advantages because of its high mineral and protein content. Protein content is highest in pearl millet. It contains a variety of important minerals, including zinc, phosphorus, and magnesium. Additionally, it includes vitamins and vital amino acids, which support its medicinal qualities.

Beneficial in treating stomach ulcers:

It is advised to consume pearl millet to treat stomach ulcers. Excessive stomach acid after eating is the most typical cause of stomach ulcers. One of the few foods, pearl millet, makes the stomach alkaline, which helps to prevent or lessen the effects of stomach ulcers.

Beneficial for Heart health:

Because millet contains powerful antioxidants including lignin and phytonutrients, heart-related disorders are prevented. Because of this, pearl millet is regarded as beneficial for heart health. It has been demonstrated that the high magnesium content of pearl millet lowers blood pressure and eases heart strain.

Reduces risk of cancer:

Pearl millet is no different from other millets in that it is known to lower the chance of developing cancer. Although they are unsure of the exact mechanism, scientists think that the high levels of magnesium and the chemical phytate are to blame.

Helps in weight loss:

Controlling one's food intake is the largest difficulty that people who are attempting to lose weight confront. Because it has a lot of fibre, pearl millet can help with weight loss. The grain takes longer to transit from the stomach to the intestines due to its high fibre content. In this manner, pearl millet helps to reduce overall food consumption by providing long-lasting satiation of appetite.

Beneficial for diabetes:

Diabetes can be effectively managed with pearl millet. Due to its high fibre content, it digests more slowly than other foods and releases glucose into the blood at a slower rate. This efficiently aids in keeping diabetic patients' blood sugar levels steady for an extended length of time.

Beneficial for Celiac Disease:

When someone has celiac disease, even a small amount of gluten in their diet is intolerable. Unfortunately, gluten can be found in the majority of common grains, including wheat, rice, and others. The only type of grain that does not contain gluten is millets. Thus, celiac disease sufferers can eat this.

Reduces Cholesterol:

It is well-known that Pearl Millet is recommended for those with excessive cholesterol levels. A type of phytochemical found in pearl millet called phytic acid is thought to boost cholesterol metabolism and stabilise blood cholesterol levels.

Beneficial in Preventing Gall stones:

Gall stone formation is also known to be decreased by pearl millet's high fibre content. The amount of insoluble fibre in pearl millet lowers our body's excessive bile production. Gall stones are frequently made worse by an excessive quantity of bile secretion in our intestines.

Anti-allergic properties:

There are a wealth of health benefits associated with pearl millet. The grain itself has a very minimal likelihood of producing allergy responses and is very digestible. It is safe to include in the diets of infants, breastfeeding mothers, the elderly, and convalescents because of its hypoallergenic qualities.

Proso Millet

Panicumm iliaceum (L.), often known as proso millet, is an annual grass that sprouts from seed every year. It is believed to have originated in Central Europe around 2000 B.C., which is at least how far back in time it can be traced. The dry regions of Central Russia, the Middle East, Northern India, Africa, Manchuria, and the Great Plains region of North America are particularly well suited to this plant. Proso millet was initially brought to Canada in the 17th century, and in the early 1900s it was only sometimes used as a forage crop.

Proso millet is a crop with few requirements, and no known diseases affect it. Because of this, Proso millet is frequently utilised in European organic agricultural practises. It is frequently utilised as an intercrop in the US. By doing so, Proso millet can assist in preventing a summer fallow and enabling continued crop rotation. Proso millet is an useful intercrop between two crops that require a lot of water and pesticides because of its shallow root system and tolerance to atrazine residue. Because the previous crop's stubbles release more heat into the soil, millet grows more quickly and early.

Kodo Millet

Throughout the tropics and subtropics of the world, Kodo millet (*Paspalum scrobiculatum* (L.)) is widely distributed in moist habitats (Fig. 6). It is an ancient Indian crop that is currently grown in Tamilnadu and Kerala in the South as well as Uttar Pradesh in the North. Other names for this cereal are varagu, haraka, and arakalu. It serves as the foundation for meeting dietary nutritional needs. It has a lot of fibre (14.3%), little fat (4.2%), and a lot of protein (11%). Kodo millet is ideal for boosting the nervous system since it is very easy to digest, has a high lecithin content, and is also very easy to digest. Niacin, B6, and folic acid, as well as minerals including calcium, iron, potassium, and magnesium, are abundant in kodo millets.Kodo millets contain no gluten and is good for people who are glutenintolerant. Regular consumption of kodo millet is very beneficial for postmenopausal women suffering from signs ofcardiovascular disease, like high blood pressure and high cholesterol levels.

Foxtail Millet

Considered a native of China, foxtail millet (*Setaria italica* (L.) P. Beauvois) is one of the oldest crops still grown today. Foxtail millet is the second most produced millet in the world and continues to play a significant role in global agriculture, giving six million tonnes of food to millions of people, mostly on marginal or poor soils in temperate, subtropical, and tropical Asia and southern Europe. It will increase in height from sea level to 2,000 metres. It cannot stand standing water. Due to its early maturity, foxtail millet can sometimes avoid droughts despite its moderate drought tolerance.It can be planted as a short-term catch crop because of its rapid growth. It can thrive in a variety of soils, climates, and elevations. Its grain is fed to poultry and caged birds as well as used for human consumption.

Barnyard Millet

Echinochlo acrusgalli (L.) P. Beauvois, sometimes known as barnyard millet, is a crop grown for food and fodder. Japanese barnyard millet, ooda, oodalu, sawan, sanwa, and sanwank are some of the other names for it. It is a good source of highly digested protein and dietary fibre with a good balance of soluble and insoluble fractions, and it is very nutritious.Barnyard millet is a natural gift from nature for today's sedentary human population because it has a low and slowly digesting carbohydrate content. Linoleic acid is the main fatty acid in barnyard millet, followed by palmitic and oleic acid. Additionally, it exhibits a strong retrogradation of amylase, which promotes the creation of more resistant starches. Therefore, it may be suggested to people who have diabetes mellitus and cardiovascular disease. The best results from barnyard millet come from lowering cholesterol and blood glucose levels.

Little Millet

India is where little millet (*Panicum sumatrense*) was domesticated. A small amount of it is grown in India up to an altitude of 2100 m, but it is not very significant elsewhere. Little millet has smaller seeds than normal millet does. With the exception of size, this cereal's species resembles proso millet in habits. It is an annual herbaceous plant that can reach heights of 30 cm to 1 m and grows either straight or with folded blades. The leaves are linear and can have membranous hairy ligules and hairy lamina.The panicles have an awn that is 2 to 3.5 mm long and range in length from 4 to 15 cm. The 1.8 to 1.9 mm long grain is smooth and rounded. It can resist both dry conditions and standing water. It may grow up to 2000 metres above sea level. Due to its early maturity and resilience to unfavourableagroclimatic conditions, little millet is another trustworthy capture crop. Stover makes excellent cattle feed.

Health Benefits of Small Millets

Small millets are very nutrient-dense and provide a number of health advantages. Below is a list of small millet's nutritional information.

- When regularly ingested, helps manage blood sugar levels. It revealed decreased LDL/VLDL and triglyceride levels.
- An increase in HDL cholesterol and cholesterol overall.
- When compared to rice, it has a lower glycemic index, which results in a more gradual rise in blood sugar levels after eating.
- The best food for persons with diabetes and digestive issues.
- Lowers the chance of a heart attack.
- Promotes the growth of body tissue and energy metabolism.
- Packed with antioxidants.

VALUE ADDITION OF MILLETS:

INSTANT MIXES

"Instant Foods" play a significant role in everyone's day-to-day existence in the modern world, as time is valuable to everyone and life moves quickly. Foods that can be consumed immediately and without further preparation are now commonplace in western nations. The development of traditional foods as convenience foods is urgently needed, and IIMR has conducted research on creating fast mixes based on sorghum, as described below.

INSTANT SORGHUM IDLI MIX

Idlis are steamed products made from rice semolina and ground pulses that are an indigenous traditional breakfast food in mostly southern Indian cuisine. They are frequently eaten with a spiced vegetable filling or chutney. Using sorghum fine semolina, blackgram dhal, salt, and food-grade additives, we tried to make instant sorghum idli mix; citric acid and sodium bicarbonate were the major ingredients. In a blender, every ingredient was thoroughly combined. A MPET packing material was used to package the prepared mixture.

Method of Preparation

<table>
<tr><td>Sorghum and Black gram dhal</td><td rowspan="11"></td></tr>
<tr><td>↓</td></tr>
<tr><td>Sieving</td></tr>
<tr><td>↓</td></tr>
<tr><td>Addition of Salt, citric acid and sodium bicarbonate</td></tr>
<tr><td>↓</td></tr>
<tr><td>Mixing</td></tr>
<tr><td>↓</td></tr>
<tr><td>Packaging</td></tr>
</table>

Benefits and Originality of Technology/Product

- Sorghum idli may be made instantly, cutting down on the laborious fermentation process.
- It has a high phenol content and induces satiety, which slows down digestion.
- Lowers oxidative stress (Antioxidant)
- The instant idli mix has a higher concentration of calcium, iron, zinc, and riboflavin when compared to control idli. • The shelf life of idli mix is three months.

Nutritional Composition of Instant Idli (100 g).

Nutrients (100g)	**Value**
Energy (kcal)	364
Carbohydrates (g)	71.7

Protein (g)	12.4
Fat (g)	1.6
Iron (mg)	7.2

INSTANT UPMA MIX

In southern Indian cuisine, upma is an indigenous traditional breakfast dish comprised of cooked semolina produced from wheat or rice with additional pulses, sauces, and spices. With the help of Bengal gram dal, sorghum semolina, mustard seeds, curry leaves, dried green chilies, salt, and oil, we attempted to make instant sorghum upma. Separate batches of semolina, mustard seeds, and Bengal gram dal were roasted. Roasted mustard seeds, Bengal gram dal, dried curry leaves, salt, and other ingredients were combined with the semolina. A MPET packing material was used to package the prepared mixture.

Method of preparation

Sorghum grits	
↓	
Roasting Bengal gram dhal and mustard seeds	
↓	
Add dried green chillies and curryleaves	
↓	
Add salt	
↓	
Mixing	
↓	
Packaging	

Benefits and Originality of Technology/Product

- Sorghum upma can be made quickly and with additional flavour and taste.
- It is safe for celiac patients and free of gluten.
- A rich source of phenolic chemicals that makes you feel full and slows digestion.
- Low-calorie diets (via dietary fibre) support good digestion and reduce oxidative stress.
- The upma mixture has a six-month shelf life.
- When compared to a traditional upma recipe, the instant upma mix contains significantly more protein, iron, and fibre.

Nutritional Composition of Instant Upma Mix (per 100 g.)

Nutrients (100 g)	Value
Energy (kcal)	374
Carbohydrates (g)	78.7
Protein (g)	13.4
Fat (g)	1.8
Fibre (g)	1.5

INSTANT DOSA MIX

Dosa is a pancake made from rice semolina and crushed pulses that is an indigenous traditional breakfast item in predominantly southern Indian cuisine. It is frequently eaten with a spiced vegetable filling or chutney. Sorghum flour, black gram dhal (2:1), salt, and citric acid and sodium bicarbonate were the key ingredients employed in our attempt to make fast sorghum dosa mix.

Method of Preparation

<table>
<tr><td>Sorghum Flour + Bengal gram dhal flour</td><td rowspan="7"></td></tr>
<tr><td>↓</td></tr>
<tr><td>Salt, citric acid and sodium bicarbonate</td></tr>
<tr><td>↓</td></tr>
<tr><td>Mixing</td></tr>
<tr><td>↓</td></tr>
<tr><td>Packaging</td></tr>
</table>

Benefits and Originality of Technology/Product

- Sorghum dosa can be made quickly and with additional flavour and taste.
- It is safe for celiac patients and free of gluten.
- A rich source of phenolic chemicals that makes you feel full and slows digestion.
- Lowers oxidative stress (Antioxidant)
- A low-calorie diet that includes dietary fibre encourages a healthy digestive system.
- The dosa mix has a six-month shelf life.
- When compared to conventional dosa, the quick dosa mix contains a high level of protein and fibre.

Nutritional Composition of Instant Dosa Mix (per 100 g.)

Nutrients (100 g)	**Value**
Energy (kcal)	364
Carbohydrates (g)	71.7
Protein (g)	12.4

Fat (g)	1.9
Calcium (mg)	10.2
Iron (mg)	7.2
Zinc (mg)	0.9

INSTANT PONGAL MIX

Information about the technology Pongal is a delectable South Indian breakfast dish that is typically made with rice and green gram. We tried to create a fast pongal mix using processed sorghum, green gram dhal, spices, and other ingredients. The mixture must be combined with three cups of boiling water, boiled in a pressure cooker for up to three whistles, and then rolled into balls with ghee or milk for serving. A MPET packing material was used to package the prepared mixture.

Method of Preparation

Millet flakes & Green gram dhal	
↓	
Addition of spices and condiments	
↓	
Mixing	
↓	
Packaging	

Benefits and Originality of Technology/Product

- Pongal can be cooked quickly and with additional flavour and taste.
- It is safe for celiac patients and free of gluten.

- A rich source of phenolic chemicals that makes you feel full and slows digestion.
- Low calorie diets (via dietary fibre) enhance healthy digestion and reduce oxidative stress.
- It combats rheumatism and arthritis
- A year's worth of shelf life.

Nutritional Instant Pongal Mix (per 100 g.)

Nutrients (100 g)	**Value**
Energy (kcal)	348
Carbohydrates (g)	69.4
Protein (g)	13.2
Fat (g)	2.1
Fibre (g)	1.54

EXPANDED PRODUCTS FROM SORGHUM

The end product of explosive puffing or gun puffing, in which the sorghum grain is stretched to its utmost extent consistent with the grain identity, is sorghum puffs (similar shape of the grain). The snack was created using a puff gun machine and is referred to as RTE (ready to eat). Dehulled sorghum grain is placed into the puff gun machine's revolving barrel, where it is combined with roasting and firing to produce puffed sorghum.

Method of Preparation

Sorghum Grain	
↓	
Grading	
↓	
Dehulling	
↓	

Dehulled Grain	
↓	
Conditioning	
↓	
Addition of water	
↓	
Puffing by Gun Puffing machine	

Advantages and Uniqueness of technology/Product

- The sorghum puffs have a shelf life of four months when stored at room temperature in airtight MET pouches and are white in colour and crispy in texture.
- They contain a significant amount of protein and fibre.
- It can be used as an evening snack or as an in-flight snack. Variations are available that are masala coated and fried as well as those that can be coated with various flours (bajra and channadhal).

Nutrient composition for puffed sorghum (per 100 g)

NUTRIENTS (100 g)	VALUE
Protein (%)	11.9
Fat (%)	3.02
Dietary fibre (g)	13.88

EXPANDED AND EXTRUDED SNACKS

Extruded Snacks are Ready-To-Eat foods made with a twin-screw hot extruder, which combines heating with the extrusion process to produce shaped cooked goods through a minuscule, circular die. In the commercial world, corn is used to make the majority of extruded snacks; in this case, sorghum grits, rice, ragi, wheat, and corn flour are used to make the extruded snack. To create enlarged, prepared-to-eat snacks, the mixture is blended and fed through a twin screw extruder. To alter the taste and flavour of the snack, desired spices can be sprinkled on top.

Method of Preparation

Millets + Rice / Corn flour
↓
Conditioning
↓
Extrusion and cutting
↓
Drying
↓
Extruded Snacks
↓
Packing

Benefits and Originality of Technology/Product

- The crisp, white to cream-colored nibbles come in a variety of colours.
- Usefulness for both in-flight and nighttime munchies.
- They include a lot of iron, zinc, magnesium, fibre, and protein.
- The product had a six-month shelf life, and shelf life analyses are still being conducted.
- Masala-coated varieties are offered.

Nutritive values of ready-to-eat extruded snack per 100 g

NUTRIENTS (100 g)	VALUE
Protein (%)	12.90
Fat (%)	1.70
Dietary fibre (g)	12.88

EXTRUDED FLAKES

Extruded Flakes are Ready-To-Eat products prepared using twin-screw hot extruder which combines heating with the act of extrusion to create round shaped product which is furtherflattened in roller flaker machine.The extruded Flakes is made from sorghum grits, wheat and corn flour. The snack can be coated with desired spices to create variations in the taste and flavor.

Method of Preparation

Millets
↓
Conditioning
↓
Roasting
↓
Roller Flaking
↓
Millet flakes
↓
Packaging

Benefits and Originality of Technology/Product

- Usefulness as breakfast cereals; they can take the place of corn flakes.
- The product had a five-month shelf life, and shelf life analyses are still being conducted.
- There are options that are masala-coated, chocolate-based, or essence-based

Nutritive values of ready-to-eat extruded flakes (per 100 g)

NUTRIENTS (100 g)	VALUE
Protein (%)	13.90
Fat (%)	1.40
Dietary fibre (g)	14.88

MILLET INSTANT LADDU MIX

Indian laddu is a ball-shaped confection prepared with flour or semolina, low-calorie sugar, and shortening. The ingredients for millet laddus are roasted sorghum fine rawa, finger millet flour, and pearl millet flour. Powdered low-calorie sugar, dry fruits, and cardamom are then added to the mixture. Before serving, the mixture must be combined with milk or ghee to form spheres.

Method of Preparation

<table>
<tr><td>Millet Composite Flour</td><td rowspan="10"></td></tr>
<tr><td>↓</td></tr>
<tr><td>Sieving</td></tr>
<tr><td>↓</td></tr>
<tr><td>Roasting</td></tr>
<tr><td>↓</td></tr>
<tr><td>Cooling</td></tr>
<tr><td>↓</td></tr>
<tr><td>Add sugar powder</td></tr>
<tr><td>↓</td></tr>
</table>

Add cardamom powder and roasted dry fruits	
↓	
Packaging	

Benefits and Originality of Technology/Product

- Laddus can be created quickly with additional flavour and taste.
- It is safe for celiac patients and free of gluten.
- A rich source of phenolic chemicals that makes you feel full and slows digestion.
- Reduces oxidative stress (antioxidant) and supports good digestion through the inclusion of dietary fibre. It also contains low-calorie sugar.
- It combats rheumatism and arthritis
- When kept at room temperature, the shelf life was three months.

SORGHUM MUESLI

A product called muesli is created by combining flakes of sorghum with honey and dry fruits. With an effort to create sorghum muesli, thick flakes were dry-roasted before being doused in honey. To this, roasted cashew nuts, almonds, pista, and raisins were added.

Method of Preparation

Sorghum flakes	
↓	
Addition of Honey	
↓	
Add Roasted Dry Fruits	
↓	
Mixing	
↓	

Muesuli	
↓	
Packaging	

Advantages and Uniqueness of technology/Product

- It is Gluten Free and Safe for Celiac Patients. • It is useful as a snack or when combined with milk. • It is a rich source of phenolic compounds and produces satiety, resulting in slower digestion.
- Lowers oxidative stress (Antioxidant)
- A low-calorie diet that includes dietary fibre encourages a healthy digestive system.
- It combats rheumatism and arthritis
- A year's worth of shelf life.

Nutritional Composition of Sorghum Muesli (100 g.)

NUTRIENTS (100 g)	VALUE
Energy (kcal)	342.4
Carbohydrates (g)	75.4
Protein (g)	17.1
Fat (g)	2.1
Fibre (g)	1.7

MILLETS VERMICELLI

Cold extrusion is the method used to make vermicelli. This technology has been acknowledged as one of the most effective in the field of food processing in recent years due to its low cost and capacity to process continuously. In the mixing compartment of the vermicelli-making machine, finger millet, foxtail millet, pearl millet, and refined wheat semolina are combined with water, blended for 30 minutes, and then extruded using a round die. The vermicelli is dried in a cabinet dryer for six hours after being left to temper at room temperature for eight hours.

Method of Preparation

Millets & Wheat flour	
↓	
Mixing	
↓	
Sieving	
↓	
Addition of water	
↓	
Extrusion and cutting	
↓	
Drying	
↓	
Cooling and Packaging	

Nutrient composition for Millets Vermicelli (per 100 g)

Nutrients (100 g)	Ragi vermicelli	Bajra vermicelli	Korra vermicelli
Protein (%)	9.39	8.39	7.65
Fat (%)	1.02	1.38	1.24
Dietary fibre (g)	1.2	1.88	1.32

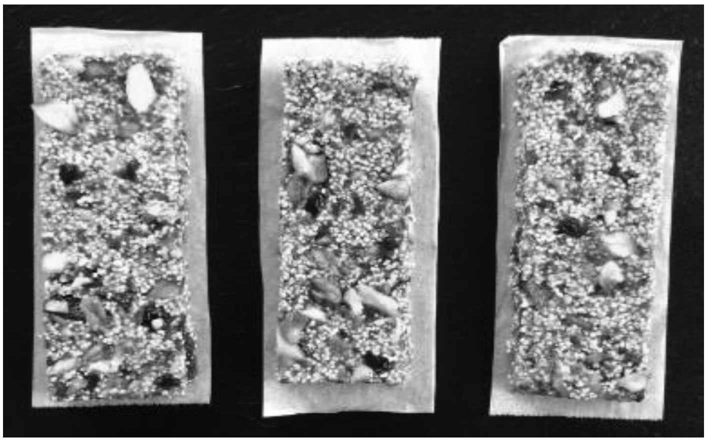
Benefits and Uniqueness of Technology/Product

- Semiya is made with it and can be made sweet or spicy.
- Studies on the shelf life of pearl millet vermicelli are currently ongoing, however finger millet vermicelli can be kept for up to six months at room temperature.

SORGHUM BASED ENERGY BARS

One of the value-added byproducts produced during the flaking of sorghum is the energy bar, which is manufactured from bran and broken flakes. To remove the moisture that is present in the bran, it is finely powdered and dried. Honey syrup was included in the product's formulation as a binder and sweetener in addition to bran and flakes. The product is a ready-to-use, healthy source of energy that may be incorporated into a regular diet or used in an emergency.

Method of Preparation

Sorghum flakes and Broken	
↓	
Mixing	
↓	
Adding of Binder and Sweetener	
↓	
Shaping	
↓	
Cooling and cutting	
↓	
Packaging	

Advantages and Uniqueness of technology/Product

- Sorghum is beneficial for athletes since it is high in dietary fibre and minerals like iron.
- Usefulness as a snack food
- The energy bars can be kept in MET pouches for two weeks at room temperature.
- It contains a lot of dietary fibre, slow-digesting carbs, and iron and zinc.

MILLETS COOKIES

Different age groups in a household like eating cookies, which are a popular ready-to-eat food. A planetary mixer, an automatic cookie maker, and a rotary oven are used to make cookies made entirely of millets. Cookies have been made at IIMR using a recipe that combines superior-quality pearl, finger, and foxtail millet flour with sugar, milk solids, trans-free fat, salt, and flavourings that are similar to those found in nature.

Method of Preparation

Millet flour	
↓	
Sugar, Vanaspathi, Milk powder, salt and flavouring	
↓	
Mixing	
↓	
Shaping and cutting	
↓	
Baking	
↓	
Cooling	
↓	
Packaging	

Advantages and Uniqueness of technology/Product

- Pure Millet biscuits are low in sugar and fat compared to market products, are high in fibre, and are healthy for all age groups.
- Magnesium, zinc, iron, dietary fibre, and protein are all abundant in it.
- It has a six-month shelf life.

MILLETS BREAD/ BUN

A RTE product called bread is made by combining a mixture of flour, water, fat, salt, and yeast, kneading the resulting dough into a loaf, and baking the loaf. At IIMR, millet breads have been created by substituting 50% of the wheat in bread with different ratios of pearl millet, finger millet, or foxtail millet flour, along with premium yeast, trans-free oil, salt, and sugar. To make bread, the dough must prove before being baked in the oven. To make buns, dough is formed into spheres then baked.

Method Preparation

Millet flour & wheat flour	
↓	
Addition of wheat	
↓	
Addition of yeast, sugar and salt	
↓	
Kneading	
↓	
Moulding	
↓	
Proofing	
↓	
Baking	
↓	
Baking	
↓	
Packaging	

Advantages and Uniqueness of technology/Product

Millet bread is useful as a morning item since it is high in protein, magnesium, zinc, iron, and dietary fibre, and it is also good for all age groups. If packaged in LDPE packages, it has a shelf life of six days.

Nutrient composition for Millets Bread (per 100 g.)

Nutrients (100 g)	Millet Bread
Protein (%)	7.4
Fat (%)	12.3
Dietary fibre (g)	0.8

MILLETS CAKE

Cake is an RTE product that is made by combining flour, sugar, fat, eggs, and flavouring ingredients until the combination becomes dough, at which point the dough is baked. At IIMR, millet cakes have been made with 100% pearl millet, finger millet, or foxtail millet flour, along with premium oil, sugar, eggs, and chocolate or vanilla essence. All the millets have also been combined in different proportions. The finger millet cake was the best of all the baked goods.

Method of Preparation

Millet flour	
↓	
Add Fat, powder sugar and egg	
↓	
Preparation Batter	
↓	
Addition of flavouring	
↓	
Baking	

↓	
Cooling	

Advantages and Uniqueness of technology/Product

- Millet cake can be used as a breakfast or snack because it is high in fibre and healthy for all ages.
- Magnesium, zinc, iron, dietary fibre, and protein are all abundant in it.
- It has a four-day shelf life when packaged in MET packets.

Nutrient composition for Millets Cake (per 100 g.)

Nutrients (100 g)	Millet Cake
Protein (%)	9.4
Fat (%)	25.3
Dietary fibre (g)	1.8

Conclusion:

Millets have been an integral part of traditional Indian diets, offering rich nutritional benefits such as high fiber, essential minerals, and low glycemic index. Their revival in modern diets supports better health outcomes, including improved digestion and management of lifestyle diseases. Value addition through innovative processing and recipes enhances their acceptability and market potential. Promoting millet-based traditional foods can contribute to sustainable nutrition, food security, and preservation of cultural heritage.

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Potential of Pearl Millet (*Pennisetum glaucum*) for Diabetes Mellitus

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Abstract

Global population growth, water scarcity and micronutrient deficiencies drive research into finding drought-tolerant crops with nutrient-rich composition and agricultural sustainability. One of these significant crops, pearl millet, can tolerate hot, dry conditions on unproductive soils with little water-holding ability. It has many functional qualities, including its low glycaemic index, possible role in weight management, and ability to reduce the risk of chronic diseases like diabetes. Diabetes mellitus has grown to be a problematic and more common health condition. Improvements in lifestyle and nutritional control are key components of treatment options for diabetes prevention. Pearl millet, one of the millets, has bioactive compounds that have various health benefits such as antimicrobial, antioxidant, antidiabetic, and hypocholesterolaemic effects, as well as hypoglycaemic activity and protection against diet-related diseases. Hence, dietary diversification of diets with millets such as pearl millet can help in combating diabetes.

Keywords: Millets, Pearl millet, Glycaemic Index, Diabetes, Dietary diversification

Introduction

Climate change presents a growing challenge to global food systems, particularly in regions vulnerable to drought and water scarcity. This shows the urgent need to explore and promote climate-resilient crops that offer both resilience and high nutritional value. Pearl millet (*Pennisetum glaucum*), a drought-tolerant grain with ancient roots in Africa and Asia, offers a compelling solution to global food security amid climate change. Its resilience in arid and semi-arid regions makes it a valuable crop for diversifying food systems and enhancing resilience in vulnerable communities worldwide.

Millets are considered “Nutri-Cereals”, “God's own crops”, “Miracle grains”, “Under-utilised”, “Cereals of the Future”, “The Future Super Food for India” and “Smart food”. They were some of the earliest plants to be domesticated, and millions of farmers in Asia and Sub-Saharan Africa still grow them as a traditional staple crop. The United Nations declared 2023 to be the International Year of Millets with the tagline "Rich in heritage, full of potential" in recognition of the nutritional and health benefits of millets (FAO, 2022). Improvements in millet consumption also target some Sustainable Development Goals (SDGs), including SDG 1 (no poverty), SDG 2 (zero hunger), and SDG 3 (excellent health and well-being) (UN, 2021).

The coarse nature of millets makes them unpopular and underutilised, despite their benefits and agro-economic potential. The availability of wheat and rice through the public distribution system, mounting per capita income, increasing urbanisation, and shifting consumer preferences are some of the factors contributing to the decline in millet consumption. As a result, refined cereals are now consumed instead of millets (Sheethal *et al.,* 2022).

Among various millets, sorghum, finger millet and pearl millet are the most significant and common millet varieties grown extensively. To promote and popularise millets worldwide, the development of newer processing methods targeted to enhance the production of value-added products is necessary. This can be achieved only by boosting the market demand and increasing the acceptability of the products in the global market. (Selladurai *et al.,* 2023).

The goal of Poshan Pakhwada 2023 was to increase knowledge of the advantages of millet for health. Using a community-based approach across India, over one crore millet-centric events have been implemented, which has produced roughly 4.89 crore activities during Poshan Pakhwada 2023. The goal of the sixth Poshan Pakhwada, which took place from March 20 to April 3, 2023, was to popularise and promote Shree Anna and millets for nutrition and wellbeing (Poshan Abhiyan, 2023).

With a proportion of almost 15% of all millet produced worldwide, India leads all other countries in this regard. In India, millets are cultivated majorly in twenty-one states in an area of 12.53 million hectares, producing 15.53 million tonnes with a yield of 1237 kg/ha. It was projected that global demand for millets will soar to $12 billion by 2025, as the world looks at healthier food grains. The global millet market was valued at US$ 9.95 billion in 2020 and is predicted to reach US$14.14 billion in 2028, growing at a CAGR of 5% from 2021 to 2028 (Kumari *et al.,* 2023).

Pearl millet (Pennisetum glaucum R. Br.) accounts for nearly 75% of the world's millet acreage. Approximately 70% of overall millet production takes place in tropical dryland climates, with Africa and Asia accounting for 98% and 97%, respectively. India is the leading producer, followed by China, Niger, and Nigeria. Between 2007 and 2019, the global area under millets decreased from 35 to 32 million ha, primarily due to a reduction in Asia. However, yields grew dramatically in Asia, from 1100 kg/ha to 1292 kg/ha, while dropping slightly in Africa. Pearl millet ranks sixth in total crops, following rice, wheat, maize, barley, and sorghum, with 50 per cent of the total world's millet production. Pearl millet, also known as Bajra, is a ubiquitous grain that can be used as a substitute for paddy, oats, quinoa, and other grain products in many cuisines (Elangovan *et al.,* 2024).

Pearl millet has been grown by farmers for ages, and replacing the regular varieties with bio-fortified crops can lessen micronutrient deficiencies in developing nations like India. Keeping this in view, various biofortified varieties of pearl millet have been released to fight iron and zinc deficiencies in India, to prevent varying degrees of impairment and complications in different human organs (Bansal and Kawatra, 2020).

Gupta *et al.* 2022 have reported that pearl millet is well adapted to production systems characterised by low rainfall (200-600 mm), low soil fertility and high temperature, and thus can be grown in areas where other cereal crops, such as wheat or maize, would not survive. In traditional growing areas, pearl millet is the basic staple for households in the poorest countries and among the poorest people. Pearl millet is generally used as a temporary summer pasture crop or in some areas as a food crop.

Despite the beneficial effects of pearl millet, over the previous three decades, millet usage as a food has drastically decreased. The main causes of its declining usage include a lack of knowledge about its nutritional benefits, difficulties in preparing meals, a lack of processing technology, and government policies that discourage the production of millet grains. Efforts were being made to scale up and optimise the utilisation of millet and its products in an attempt to realise and derive the benefits thereof (James *et al.,* 2022).

Diabetes mellitus (DM) is a metabolic disorder characterised by hyperglycemic conditions resulting from inadequate insulin production or sensitivity. Globally, the prevalence of DM is drastically increasing, especially in low-and middle-income countries. Therefore, there is a need to explore effective DM management strategies (Kumar 2025).

According to the WHO, "diabetes is a chronic disease that occurs either when the pancreas does not produce enough insulin or when the body cannot effectively use the insulin it produces" (WHO 2023). A chronic elevation in blood glucose level may damage various organs such as the nerves, kidneys, eyes, and heart. It has been found that approximately 90% of diabetic patients have T2DM, in which either pancreatic-β cells cannot produce enough insulin or/and tissues become insulin resistant. Studies have suggested that the pathogenesis of DM includes adipokine dysregulation, chronic low-grade inflammation, gut dysbiosis, and immune system dysregulation (Galicia-Garcia *et al*. 2020). Understanding these factors is crucial for developing an effective T2DM management strategy.

The current recommendations for type-2 diabetes are to adopt safe, nutritious diets, particularly with low-GI (glycaemic index) starchy carbohydrates and elevated dietary fibre that can help control post-prandial hyperglycaemia and minimise body weight. A low glycaemic carbohydrate/high fibre diet has been shown to successfully lower plasma cholesterol and enhance blood glucose balance for type 2 diabetes (Willett *et al.* 2002).

Production, availability, consumption and trade of pearl millet

Kumari *et al.* (2023) documented that India is the global leader in the production of millets with a share of around 15% of the world's total production. In India, millets are cultivated majorly in 21 states in an area of 12.53 million hectares, producing 15.53 million tonnes with a yield of 1237 kg/ha. It is estimated that global demand for millets will soar to $12 billion by 2025, as the world looks at healthier food grains. The global millet market was valued at US$ 9.95 billion in 2020 and is projected to reach US$14.14 billion in 2028, growing at a CAGR of 5% from 2021 to 2028.

According to Deevi *et al.* (2024), among the millets, pearl millet (*Pennisetum glaucum R. Br.*) represents approximately 75% of the global millet area. Around 70% of total millet is produced under warm tropics dryland climates with Africa and Asia accounting for 98% of the global area and 97% of global production. Among the countries, India is the largest producer followed by China, Niger, and Nigeria. The area under millets has come down globally from 35 to 32 million ha between 2007 and 2019 mainly due to the decline in Asia. However, yields increased significantly in Asia from 1100 kg/ha to 1292 kg/ha while declining marginally in Africa.

Globally, nearly 3/4 of the domestic supply of millet is used for food, and the rest is used for feed and other uses. Developed countries mainly use millet for animal feed/bird feed. Millets are thinly traded, with less than 2% of total millet production being exported. Despite this, global millet demand is set to increase from 48.5 to 66.5 million tons between 2030 and 2050, and in Asia, the projected supply would be lower than the demand, indicating a widening gap with scope for enhanced trade to meet the shortfall.

The production of pearl millet has also increased from 8.07 million tonnes to 10.86 million tonnes from 2015-16 to 2020-21. The State Governments can also promote the cultivation of millets under Rashtriya Krishi Vikas Yojana – Remunerative Approaches for Agriculture and Allied sector Rejuvenation (RKVYRAFTAAR) with the approval of the State Level Sanctioning Committee (SLSC) (Kumari *et al.,* 2023).

Through the efforts made by the Government, the production of millet has increased significantly in recent years. Several efforts have been made over the last few years to realign the Minimum Support Price (MSP) to encourage farmers to shift to larger areas and adopt the best technologies and farm practices, to correct the demand-supply imbalance (Ministry of Information and Broadcasting, 2023). There has been a significant rise in the MSP of pearl millet.

Globally, trade in millets is very thin, with less than 2% of total production being traded. This reveals their importance as a self-sufficient crop in respective regions/countries. Traded volumes among countries have increased marginally from 0.2 million tons during 1980–1982 to 0.4 million tons by 2017–2019. Historically, the leading exporters in the world are India and the USA. India's exports largely comprise pearl millet. In India, the inter-state trade movement of pearl millet from major pearl millet growing states to primarily other urban centres has been observed. Pearl millet grain is exported from Gujarat and Uttar Pradesh to Rajasthan in years when there is drought in Rajasthan. Trade also happens within Rajasthan and with the eastern regions supplying grain to the western regions of the state. Alcohol industries in Haryana and Punjab import grain from Gujarat and Rajasthan when there is surplus production there (Deevi *et al.,* 2024).

Nutritional composition of pearl millet

Pallavi *et al.* (2023) stated that pearl millet is considered the cheapest and richest source of energy, protein, iron and zinc among all cereals and pulses with a metabolizable energy of 2900

Kcal, starch content of 62–68%, protein content of 7.3–13.86% and fat content of 4.36– 7.11%. Antioxidant activity of pearl millet hybrids and varieties is higher than that of fine cereals. Fibre content in pearl millet has been reported to be 1.6 g/100 g. Hence, substituting this nutrient-rich millet with routine foods like rice and wheat in India will help in tackling the problems of malnutrition, hidden hunger, obesity, celiac disease, diabetes, etc.

In India, pearl millet is considered a primary source of dietary energy (360 k.cal/100g) for rural populations in drier parts of the country. It is a rich source of protein, fat, calcium, phosphorus, and iron. Pearl millet comprises a fairly high amount of thiamine, riboflavin and niacin. The energy level is highest among whole grain cereals. It is nutritionally comparable and superior to many cereals (Gupta *et al.,* 2022).

Sachan and shah (2023) evaluated proximate composition, Mineral content and Antioxidant compounds of pearl millet flour. And revealed that the moisture content was 10.70±0.10, the ash content was 1.23±0.01 g/100 g and the crude protein content was 8.40±0.10 g/100 g. The value of the mineral content of Iron 14.70±0.03 µg/mg, Zinc 01.84±0.01 mg/100 g and calcium content of 16.26±0.02 mg/100 g. The antioxidant analysis was performed. The total carotenoid content0.44±0.003 mg/100 g, DPPH Activity 31.87±2.0 QDE/g of dw and Ferric ion Reducing Antioxidant Power 11.2±0.005 FSE/g of dw in pearl millet flour. Results indicate that pearl millet is a good source of protein, dietary fibre, iron, zinc, and calcium.

Bello *et al.* (2022) stated that pearl Millet (*Pennisetum glaucum*) is a good source of dietary and health-promoting compounds compared with the main cereals grown. Nevertheless, significant factors restricting its use are anti-nutritional factors (phytate, tannins, and oxalic acid), responsible for poor mineral availability and low sustaining consistency due to higher lipase activity. Many of the wild relatives have adapted to overcoming floods, extreme heat, cold, and drought, thus modifying or establishing resistance to pests and diseases, resulting in less significant crop losses. Because of its unusually high nutrient content, pearl millet is valuable and contains high amounts of protein, magnesium, B vitamins, zinc, potassium, phosphorus, calcium, and fats. Besides, high levels of dietary fiber are present, which contribute much more to the health benefits of this important grain.

Nutritional Characteristics of pearl millet genotypes of India (Vinutha *et al.,* 2022) are depicted in Table 1.

Table 1. Nutritional characteristics of pearl millet genotypes in India (Vinutha et al., 2022)

	Carbohydrate					Protein			Minerals	
Pearl millet Landraces	Starch (%)	Starch Quality				Protein (%)	Protein Quality		Fe (ppm)	Zn (ppm)
		Reducing Sugars (%)	Amylose (%)	Resistant starch (%)	In vitro glycaemic potential		Protein Digestibility (%)	Essential amino acid content (%)		
Jafrabadi (Gujrat)	67.80	2.75	27.77	1.42	77.05	12.25	47.04	36.94	56.66	50.0
Chanana Bajri (Rajasthan)	61.78	0.72	25.87	2.58	69.03	12.54	51.14	38.56	37.00	33.0
Chadi-Bajri (Rajasthan)	58.97	0.70	24.08	2.09	61.11	12.25	55.15	34.75	39.00	30.0
Damodar Bajri (Rajasthan)	59.75	0.67	23.56	1.83	55.10	10.50	58.82	34.00	35.00	34.0
Pusa 1201 (Pusa Hybrid)	59.96	2.30	-	2.87	61.5	15.45	45.81	63.27	56.00	45.0
Dhanshakti (ICRISAT - Composite)	57.51	2.76	24.50	1.95	67.8	11.66	47.62	33.97	83.00	44.0

Pearl Millet and Its Diabetic Implications

The diet plays a vital role in maintaining blood glucose by modulating the absorption of nutrients or the secretion and action of insulin. The plants are a potential source of phytochemicals, including plant-derived peptides, flavonoids, glycosides, phenolic compounds, terpenoids, and alkaloids, which have antidiabetic potential (Ansari et al. 2021). In this context, millets are promising candidates for dietary incorporation because of their nutritional benefits and adaptability. They can thrive in adverse environmental conditions such as water scarcity, drought, high temperatures, and high salinity. They are considered "smart crops" and contribute to UN SDGs. Millets contain complex carbohydrates, fiber, vitamins, minerals, and bioactive compounds. The diverse nutritional composition of millet highlights that it can be used as a staple food with potential health benefits, such as improved glycemic control, lipid profiles, haemoglobin concentrations, cognitive performance and iron status, and gut microbiota (GM) composition (Kumar *et al*. 2024).

The high dietary fiber content and slow digestion rate make it an effective food for supporting weight management by promoting satiety and reducing excessive calorie intake. Moreover, its nutritional value can be significantly enhanced through food processing techniques such as dehulling and fermentation, which have been shown to improve protein digestibility and reduce anti-nutritional factors. These processing methods not only enhance the bioavailability of essential nutrients but also contribute to better glycemic control and overall health outcomes (Sharma 2025).

Pearl millet contains phenolic compounds that possess antidiabetic activity. Thus, it can be used to prepare a variety of food products for diabetes mellitus. Moreover, it also has many health benefits, including combating diabetes mellitus, cancer, cardiovascular conditions, decreasing tumour occurrence, lowering blood pressure, heart disease risk, cholesterol, and fat absorption rate. Diet is known as the centrepiece of diabetes mellitus treatment, especially important in the case of non-insulin-dependent diabetes mellitus (NIDDM), which involves the metabolism of glucose and secondary lipid and protein deficiencies as the primary derangement (Pei *et al.* 2025). Diabetes dietary treatment includes reducing postprandial hyperglycaemia and strong glycaemic control. Mani et al. (1993) stated that pearl millet (*Pennisetum typhoideum*) has the lowest GI compared to varagu alone in addition to complete green grams (Phaseolus aureus Roxb), jowar (Sorghum vulgare), and ragi (Eleusine coracana). Low-glycaemic foods are beneficial for enhancing the metabolic regulation of blood pressure and low-density plasma lipo protein cholesterol, leading to less prominent insulin reactions (Asp. 1994). Several new food items based on pearl millet can be created, and conventional recipes for diabetic patients need to be supported.

The starch content in various pearl millet genotypes ranges from 62.8 and 70.5%, soluble sugar between 1.2 and 2.6%, and amylose between 21.9 and 28.8% (Dasa and Nguyen 2020). In some high-yielding Indian pearl millets, lower starch (56.3 to 63.7%) and amylose (18.3 to 24.6%) values were found (Bhupender *et al*. 2013). The key portion of overall soluble sugar (2.16 to 2.78%) was sucrose (66%), followed by raffinose (28%) (Giannoccaro *et al.* 2006). Stachyose, glucose, and fructose were other sugars found in measurable quantities. The percentage of overall sucrose in pearl millet was smaller than that of sorghum. The total dietary fibre of pearl millet (20.4%) and finger millet (18.6%) is higher than that of sorghum (14.2%), wheat (17.2%), and rice (8.3%), and the total dietary fibre content of pearl millet was 17% (Kamath and Belavady 1980).

Pearl millet helps to keep blood sugar levels stable for a long time in diabetic patients. It is also helpful for diabetes patients because it has a comparatively small glycaemic index that helps steadily digest and contain glucose at a slower pace than other foods (Saini *et al.,*2021). This will help maintain healthy blood sugar levels for long stretches. The amylase activity of pearl millet is very high, about 10 times that of wheat. Maltose and D-ribose are the major sugars in the flour, and are low in fructose and glucose (Dias-Martins *et al.* 2018).

Sukar et al. (2020) showed substantial elevation of adiponectin associated with a vast decrease in blood glucose levels during the study periods. These findings imply that feeding with the whole grain of pearl millet, a diet, can play a significant role in restoring the plasma level of adiponectin to the physiological level. It is well established that an increase in adiponectin level stimulates glucose utilisation through the activation of AMP-activated protein kinase in the skeletal muscle and liver (Kadowaki *et al.* 2006), and such a diet containing pearl millet could reduce glucose level due to an enhancement of the utilisation of glucose by peripheral tissues and the elevation of adiponectin levels. Many theories support the hypoglycaemic effects of pearl millet, such as the theory that its richness in phytate and phenolic compounds reduces fasting hyperglycaemia and attenuates postprandial blood glucose response in rats. Phenolic compounds are also known to enhance insulin activity, and pearl millet regulates intestinal GLUT, increases muscle glucose uptake, and reduces hepatic gluconeogenesis.

Some in vivo experiments were performed to research the effect of pearl millet grains on diabetes. In one research, the impact on glucose and insulin responses in diabetic people was assessed in six typical Sudanese carbohydrate-rich meals. A slightly lower response to postprandial glucose and insulin was shown for pearl millet acid (porridge) followed by wheat gorasa (pancakes), while maize acid triggered a higher postprandial glucose and insulin response (Adéoti *et al*. 2017). Another study showed substantially decreased levels of non-enzymatic antioxidants (glutathione, vitamin E, and vitamin C), enzymatic antioxidants (superoxide dismutase, catalase, glutathione peroxidase, and glutathione reductase), and lipid peroxides of diabetes in normal amounts compared to pearl millet-fed populations (Nani *et al.* 2015). Therefore, pearl millet is also very effective in diabetes management. It gradually digests and contributes glucose to the blood at a higher rate relative to other foods due to its high fibre content. This helps to maintain a steady blood sugar level in diabetic patients for a long time.

Conclusion

Pearl millet, one of these important crops, can withstand hot, dry weather on unproductive soils with poor water-holding capacity. People with diabetes benefit greatly from pearl millet. It helps those with diabetes and is a wonderful source of vitamins and minerals. It is still primarily limited to rural communities. Including more nutrient-dense, traditional whole-grain and multigrain substitutes for processed carbs may be a key component of therapeutic dietary changes and the promotion of pearl millet use. Nutritional insecurity among vulnerable populations, particularly those with diabetes, can be decreased by dietary diversity with micronutrient-rich cereals like millets, which are thought to be underutilised grains.

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Role of Positive Psychological Factors in Diabetes Management

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Abstract

Insufficient production, impaired insulin response, or both, resulting in elevated blood sugar levels, are hallmarks of a long-lasting metabolic disease, namely diabetes mellitus. The consequences of diabetes are not limited to the lower quality of life but also result in global morbidity and financial costs. An individual's proneness to diabetes has been observed due to the following factors such as sedentary lifestyle, age, family history, hypertension, dyslipidemia (abnormal lipid profiles), gender, and unhealthy diet. Diabetes can be understood under two major categories, Type 1 (an autoimmune condition that causes the death of cells that produce insulin) and Type 2 (a common worldwide condition associated with insulin resistance). Effective diabetes management involves more than just diet and medication; psychological factors such as adaptive coping, emotional regulation, hope, optimism, resilience, and self-efficacy not only help in regulating blood sugar status but also decrease diabetes-related distress.

Keywords: Diabetes Mellitus, Positive Psychological factors, Diabetes Management

Introduction

Diabetes Mellitus

Diabetes mellitus (DM) ranks among the most prevalent endocrine disorders worldwide and poses a serious public health concern, leading to considerable illness, death rates, and substantial economic costs (Ibrahim, 2019). Diabetes mellitus is "a chronic and progressive metabolic condition defined by sustained hyperglycemia (high blood glucose levels), irregular insulin production, insulin function, or both combined" (American Diabetes Association, 2010).

Raisoddin & Ukkali (2024) defined "diabetes mellitus as a prevalent non-communicable disease characterized by high blood sugar levels due to insufficient insulin production or ineffective insulin response". Diabetes mellitus can be understood under two major categories, *viz*., Type 1 Diabetes Mellitus (damage of insulin-producing cells due to an autoimmune condition) and Type 2 Diabetes Mellitus (results due to insulin resistance and is more prevalent universally).

Hjelm et al. (2003) stated that DM constitutes a disturbing health concern worldwide, with its occurrence continuing to increase and evolving into a pandemic. Global evaluations from WHO projected that the number would reach 366 million by 2030 (Wild et al., 2004).

Research findings reported multiple reasons behind the illness, including sedentary lifestyle (Hermawan et al., 2024), age (Afifah et al., 2022), family history (Ginting et al., 2023; Fin et al., 2025; Ibrahim & Borja, 2025), hypertension (Hermawan et al., 2024), dyslipidemia (abnormal lipid profiles), smoking (Mayasari & Indahyati, 2021), gender (male), and obesity (Patil & Gothankar, 2019). Also, an unhealthy diet, particularly a high intake of fast foods and sugary beverages, has been identified as a promising factor contributing to the predisposition to diabetes mellitus Type 2 (Ibrahim & Borja, 2025; Afifah et al., 2022).

Diabetes not only has an impact on the person, their families, and healthcare systems, but the enduring form of diabetes, combined with the risk of severe complications, frequently imposes a heavy financial pressure and substantially lowers quality of life (Coffey et al., 2002). Also, when blood glucose level is not adequately controlled, it commonly leads to severe difficulties, including cardiovascular disease, stroke, hypertension, vision loss or blindness, kidney failure, neuropathy (nerve damage), lower limb amputations, and early mortality (Stratton et al., 2000).

Positive Psychological Factors

Emphasis on lifestyle changes, including diet, exercise, and adherence to treatment (Nautiyal & Nautiyal, 2014), oral hypoglycaemic agents, and insulin therapy should be ensured to manage diabetes mellitus effectively (Omar, 1987). Also, knowledge and the complications associated with the disease will help manage blood glucose levels (Imam, 2013).

However, managing diabetes effectively goes beyond physical aspects like medication and diet; incorporating positive psychological factors can decrease diabetes-related distress, develop self-management, and lower the risk of problems.

Below is a summary of positive psychological factors and their contribution in managing diabetes mellitus:

Adaptive Coping

Coping refers to constructive ways of dealing with stress, challenges, or difficult emotions that help one address the problem (or one's response to it) effectively, resulting in better health outcomes. Coping styles have been divided into two major types (maladaptive and adaptive). Maladaptive coping strategies involve avoidance behaviors that do not provide long-term benefits to the individual. In contrast, adaptive coping strategies address the stressor directly and seek to alleviate emotional distress (Ye et al., 2020). Multiple studies found that adopting adaptive coping strategies (objective planning, seeking healthy social networking, accepting the situation, adhering to treatment, borrowing insulin, and overcoming storage barriers) helps control the complications of Type 1 diabetes mellitus (Owusu et al., 2023). Also, adaptive coping strategies (self-management, goal-setting, social networking, emotional support) help control blood glucose level (Conduah et al., 2025) and overcome stress related to diabetes and contribute to better glycaemic control (Lau et al., 2021). Actively seeking to control their diabetes through advice from healthcare professionals and support from peers (Kumar & Kohli, 2024; Stuckey et. al., 2014) also helps in managing the blood glucose levels, develops a better self-care attitude (Miles et al., 2018), resulting in a healthy quality of life (Hapunda, 2022).

Emotional Regulation

Referring to Gross (1998) "emotion regulation is the processes by which individuals influence which emotions they have, when they have them, and how they experience and express them". An inverse relationship has been observed between diabetes distress and emotional regulation (Coccaro et al., 2021), improved psychological well-being, and better health (Rahmania et al., 2020). Furthermore, managing diabetic discomfort and unhealthy eating patterns in individuals with Type 1 diabetes can be achieved with the help of emotion regulation methods (expressive suppression and cognitive reappraisal) (Embaye et al., 2023). Addressing emotional dysregulation helps maintain self-management behaviour (Kollin et al., 2024). Also, emotional regulation serves an imperative role in managing diabetes mellitus, principally in mitigating distress associated with diabetes mellitus and adhering to treatment and self-management behaviors of Type 2 diabetes mellitus (Miller et al., 2022).

Hope

According to Snyder (2002) “hope is the perceived capability to derive pathways to desired goals, and motivate oneself via agency thinking to use those path”. Fostering an internal locus of hope, particularly through family support, has been shown to enhance life satisfaction and motivate goal attainment in diabetes management (Coban-Tosyali & Bozo, 2026) among Type 2 Diabetes Mellitus patients. Hope-based interventions effectively reduce stress and enhance hope and subjective well-being in individuals with Type 2 Diabetes Mellitus, suggesting that fostering hope can be a valuable strategy in managing diabetes psychologically (Sosialita & Hamidah, 2015). Also, patients with high hope showed better blood glucose levels and lower depression (Santos, 2015).

Optimism

In the view of Carver et al. (2010), “optimism is an individual difference variable that reflects the extent to which people hold generalized favorable expectancies for their future”. Research indicates that fostering an optimistic outlook not only enhances self-management behaviors but also improves the health conditions of patients with the said diseases. Highly optimistic people suffering from diabetes mellitus apply problem-focused coping style to control blood sugar levels and adhere to self-management behaviour (Celano et al., 2013), enabling patients to face challenges with realistic optimism and independence (Lombardo et al., 2003) resulting in reduced anxiety (Cahyani, et al., 2020), psychological distress (Ravindran et al., 2022), stress-related neuroendocrinal changes (Molavi et al., 2019), and treatment adherence (Celano et al., 2013) and health outcomes (Meldgaard et al., 2022). Better blood sugar level, higher life expectancy (Massey et al., 2017), consistency in self-care behaviour has been observed among optimistic people suffering from Type 2 diabetes mellitus (Zhao et al., 2020; Karl et al., 2020). Optimism can lead to "benefit finding," where patients identify positive changes in behavior, relationships, and spirituality after a diabetes diagnosis, motivating them to follow healthier lifestyle choices (Karimi Moonaghi et al., 2014).

Resilience

As stated by APA (American Psychological Association) (2014), “resilience is 'the process of adapting well in the face of adversity, trauma, tragedy, threats or even significant sources of stress.” Among patients suffering from diabetes mellitus, resilience helps moderate the negative impact of adherence to a balanced diet, exercise, stress management, and medication adherence. In a research, Kusnanto et al. (2020) found that resilience, social networking, and self-care are some of the significant variables helping in managing diabetes mellitus (Type 2). Resilience is significantly correlated with better glycemic outcomes (lower HbA1c) and reduced mental health issues (anxiety, depression, and diabetes-related distress) in adults diagnosed with type 1 diabetes (O’Daffer et al., 2024). Also, resilient individuals with DM can manage stress objectively (Yi-Frazier et al., 2024) and regulate emotional distress (Patel et al., 2022), resulting in better psychological health and enhanced quality of life (Julceus et al., 2024). According to Araujo et al. (2024), resilience enhances self-care behaviors, particularly in food and foot care, and managing blood sugar levels. In an investigation, Omar et al. (2023) posited that resilience in managing diabetes among Arabic-speaking refugees is driven by self-reliance, facilitated by awareness about the disease, self-care, and a positive attitude towards the disease.

Self-efficacy

Bandura (1997) states, “self-efficacy as 'beliefs in one’s capability to organize and execute the course of action required to produce given attainments”. In the milieu of diabetes management, when a patient with diabetes mellitus engages in diabetes-related behaviours such as regularly checking the blood sugar levels, adhering to a strict diet plan, and adhering to treatment, they are considered highly self-efficacious. A highly self-efficacious patient with diabetes mellitus (Mohebi et al., 2013) is seen as better able to control their diabetes constructively (Dehghan et al., 2017; Qin et al., 2020) by consuming a balanced diet, controlling blood glucose level, and taking proper treatment (Al-Khawaldeh et al., 2012). Educational workshops (Krichbaum et al., 2003) practising and recording self-management skills, peer models, timely reinforcement, and healthy feedback from health providers have been reported to enhance self-efficacy and overcome the complications associated with diabetes mellitus (Jiang et al., 2019).

Chapter Summary

- Diabetes mellitus (DM) ranks among the most prevalent endocrine disorders worldwide, driven by both genetic and lifestyle factors, leading to serious health complications including cardiovascular disease, stroke, hypertension, vision loss or blindness, kidney failure, neuropathy (nerve damage), lower limb amputations, and early mortality.

- Factors such as unhealthy diet, including high intake of fast foods and sugary beverages, sedentary lifestyle, age, and family history increase the likelihood of diabetes mellitus.
- Managing diabetes effectively goes beyond physical aspects like medication and diet; incorporating positive psychological factors can decrease diabetes-related distress, develop self-management, and lower the risk of problems.

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Diabetes Across the Lifespan: Children, Adolescent, And Elderly

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1. Introduction

Diabetes mellitus (DM) is a chronic metabolic disorder characterized by persistent hyperglycemia resulting from defects in insulin secretion, insulin action, or a combination of both. Hyperglycemia, if prolonged, causes progressive damage to multiple organ systems, including the retina (diabetic retinopathy), kidneys (diabetic nephropathy), peripheral nerves (diabetic neuropathy), heart (cardiovascular disease), and blood vessels (atherosclerosis)**.** These complications contribute significantly to morbidity and mortality among affected individuals **(American Diabetes Association, 2026).**

Traditionally considered a disease of adults, diabetes is increasingly being recognized across all age groups, including children, adolescents, and the elderly**,** due to a combination of genetic susceptibility, environmental factors, and lifestyle changes. The global prevalence of diabetes is rising rapidly: childhood and adolescent obesity, sedentary behavior, and urbanization have contributed to a surge in Type 2 diabetes among the younger population, while aging populations and associated comorbidities have increased diabetes incidence in the elderly **(Mayer-Davis et al., 2023; Sinclair et al., 2021).**

1.1 Diabetes in Children and Adolescents

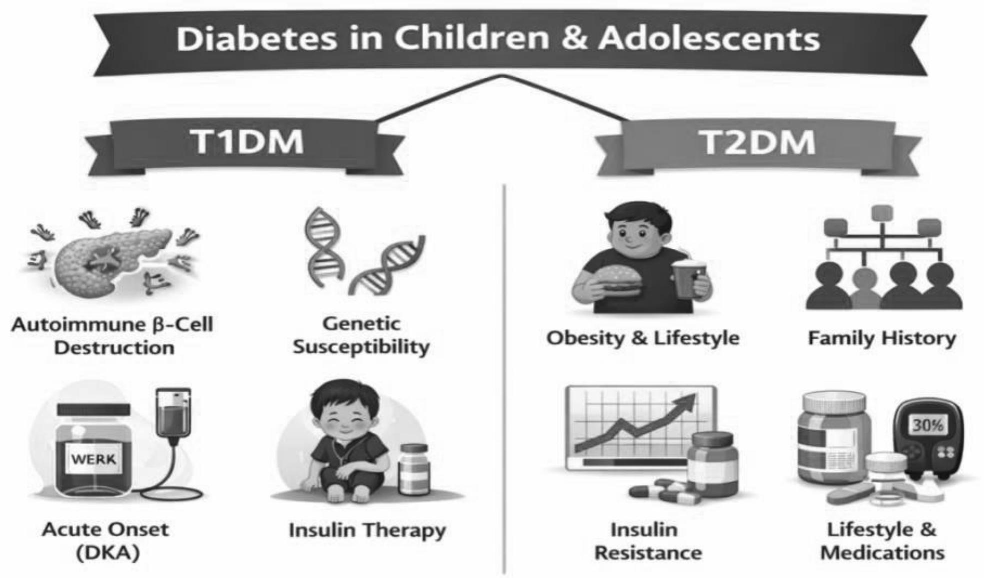
In children and adolescents, both **Type 1 Diabetes (T1DM)** and **Type 2 Diabetes (T2DM)** are of concern:

- **T1DM** arises primarily from autoimmune destruction of pancreatic β-cells**,** leading to absolute insulin deficiency. It is the most common form in children and typically presents acutely, often with polyuria, polydipsia, weight loss, and diabetic ketoacidosis (DKA) in severe cases. Genetic factors, particularly HLA-DR3 and HLA-DR4 alleles**,** contribute to susceptibility **(Atkinson & Eisenbarth, 2020).**
- **T2DM** is increasingly recognized in adolescents due to obesity, poor dietary habits, and sedentary lifestyle**,** resulting in insulin resistance and relative insulin deficiency**.** Early clinical manifestations may be subtle, including overweight/obesity, acanthosis nigricans, fatigue, and mild hyperglycemia, often detected incidentally during routine examinations. Management involves lifestyle modification, pharmacotherapy (metformin), and insulin if glycemic targets are unmet **(Mayer-Davis et al., 2023).**

Other forms of diabetes in youth include:

- **Monogenic Diabetes (MODY):** Genetic mutations affecting β-cell function, usually autosomal dominant.
- **Secondary Diabetes:** Associated with cystic fibrosis, pancreatitis, steroid use, or other endocrine disorders.

Figure 1.1: Classification of Diabetes in Children and Adolescents



1.2 Diabetes in the Elderly

In elderly populations, **Type 2 Diabetes (T2DM)** is the predominant form, often complicated by **comorbid conditions** such as cardiovascular disease, hypertension, chronic kidney disease, and cognitive impairment.

- **Pathophysiology:** Age-related β-cell dysfunction, insulin resistance due to visceral fat, and chronic low-grade inflammation contribute to hyperglycemia.
- **Clinical Presentation:** Symptoms are often a typical or nonspecific**,** including fatigue, recurrent infections, polyuria, or cognitive changes. Hyperosmolar hyperglycemic state (HHS) may be the initial manifestation.
- **Management Considerations:** Focus is on avoiding hypoglycemia**,** controlling comorbidities, and preserving quality of life. Pharmacotherapy must be tailored considering renal function, cardiovascular status, and frailty **(Sinclair et al., 2021).**

Table 1.1: Comparison of Diabetes in Youth vs. Elderly

Feature	Children & Adolescents	Elderly
Predominant Type	T1DM > T2DM	T2DM
Onset	Rapid (T1DM), gradual (T2DM)	Gradual
Common Symptoms	Polyuria, polydipsia, weight loss	Fatigue, mild polyuria, infections
Acute Complications	DKA common	HHS possible, hypoglycemia risk
Chronic Complications	Rare initially	High (retinopathy, nephropathy, CV disease)
Management Focus	Insulin therapy, lifestyle	Individualized therapy, comorbidity management

1.3 Importance of Age-Specific Management

Diabetes management requires **age-tailored approaches**:

- **Children and Adolescents:** Emphasize early recognition, insulin therapy, family involvement, school-based education, and prevention of acute complications**.**
- **Elderly:** Focus on individualized glycemic targets, safe pharmacotherapy, prevention of hypoglycemia, and maintenance of independence and quality of life.

Early recognition, patient and family education, lifestyle interventions, and use of modern technologies such as continuous glucose monitoring (CGM) and insulin pumps improve outcomes and reduce morbidity across all age groups.

Table 1.2: Key Differences Between Diabetes in Children, Adolescents, and Elderly

Aspect	Children & Adolescents	Elderly
Type of Diabetes	T1DM predominant; T2DM rising	T2DM predominant
Onset	Rapid (T1DM), gradual (T2DM)	Gradual
Insulin Requirement	Lifelong for T1DM, sometimes T2DM	Varies, often oral agents first
Acute Complications	DKA	HHS, hypoglycemia
Chronic Complications	Rare initially	High, compounded by comorbidities
Management Approach	Family-centered, insulin + lifestyle	Individualized, comorbidity-focused
Screening Needs	High-risk obesity, family history	Routine age/comorbidity-based

2. Classification of Diabetes by Age

Diabetes mellitus can affect individuals at any age, but the clinical features, pathophysiology, and management vary significantly depending on the age group. Understanding age-specific classifications is crucial for accurate diagnosis and effective management.

2.1 Diabetes in Children and Adolescents

In children and adolescents, diabetes primarily presents as:

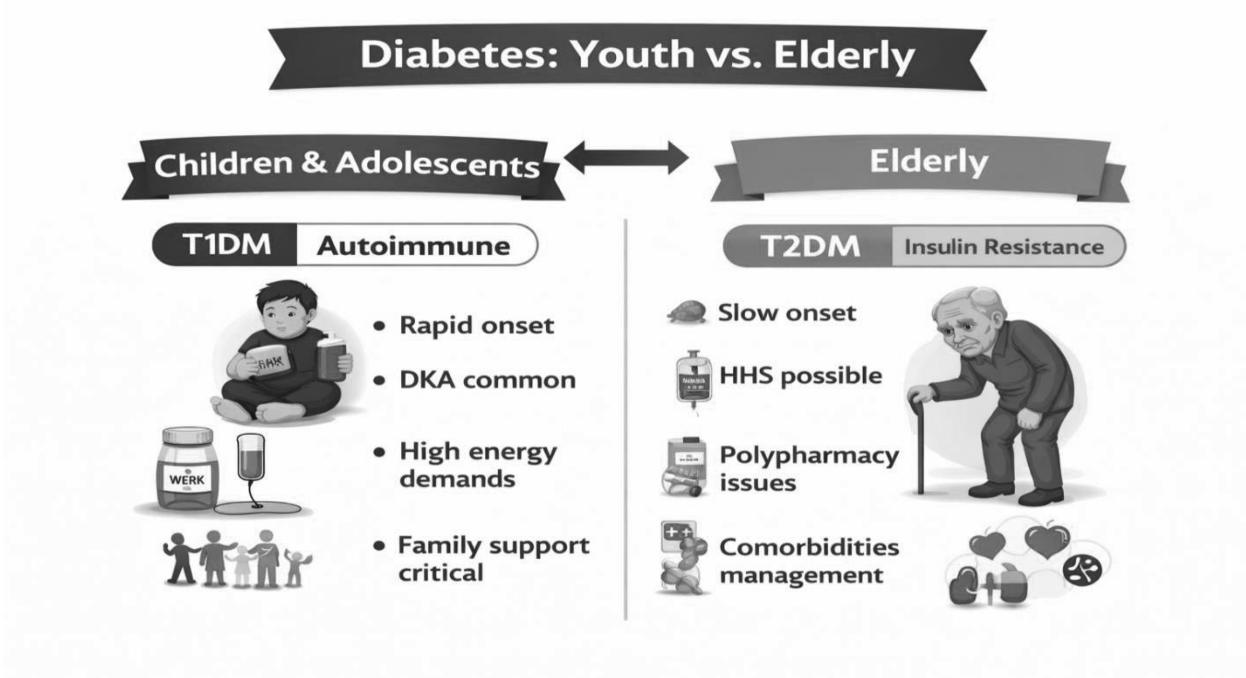
- **Type 1 Diabetes (T1DM)**
    - **Etiology:** Autoimmune destruction of pancreatic β-cells leading to absolute insulin deficiency.
    - **Epidemiology:** Most common form of diabetes in children, with incidence peaking at ages 4–7 years and 10–14 years.
    - **Clinical Features:** Polyuria, polydipsia, weight loss, fatigue, and in many cases, diabetic ketoacidosis (DKA) at presentation.
    - **Genetic Factors:** Associated with HLA genotypes (HLA-DR3 and HLA-DR4).
    - **Management:** Lifelong insulin therapy is mandatory **(ADA, 2026).**
- **Type 2 Diabetes (T2DM)**
    - **Etiology:** Combination of insulin resistance and relative insulin deficiency.
    - **Epidemiology:** Increasingly common in adolescents due to obesity, sedentary lifestyle, and poor dietary habits.
    - **Clinical Features:** Often subtle, with obesity, acanthosis nigricans, mild hyperglycemia, or incidental detection.
    - **Management:** Lifestyle modification, metformin therapy, and insulin if glycemic targets are not met.
- **Other Forms of Diabetes in Youth**
    - **Monogenic Diabetes (MODY):** Genetic mutations affecting β-cell function, usually autosomal dominant inheritance.
    - **Secondary Diabetes:** Associated with conditions like cystic fibrosis, pancreatitis, steroid use, or endocrine disorders.

2.2 Diabetes in the Elderly

In elderly individuals, diabetes is predominantly **Type 2**, often accompanied by other age-related comorbidities:

- **Pathophysiology:**
    - Decreased insulin secretion due to β-cell dysfunction
    - Increased insulin resistance due to aging, visceral fat, and chronic inflammation
- **Clinical Presentation:**
    - Often atypical or nonspecific: fatigue, recurrent infections, polyuria, cognitive decline
    - Hyperosmolar hyperglycemic state (HHS) may be the first manifestation
- **Management Considerations:**
    - Focus on avoiding hypoglycemia, managing comorbidities, and preserving quality of life
    - Pharmacotherapy tailored based on renal function, cardiovascular status, and frailty **(Sinclair et al., 2021)**

Figure 2.1 Diabetes: Youth vs. Elderly



2.3 Key Points

- Children/adolescents: T1DM predominates but T2DM is rising.
- Elderly: Mostly T2DM with complex comorbid conditions.

- Age-specific management strategies are essential to improve outcomes.

3. Pathophysiology of Diabetes in Children, Adolescents, and Elderly

Diabetes mellitus (DM) is characterized by chronic hyperglycemia resulting from defects in insulin secretion, insulin action, or both. Persistent hyperglycemia leads to metabolic dysregulation, oxidative stress, and microvascular and macrovascular complications over time. The pathophysiological mechanisms of diabetes vary significantly across age groups, affecting onset, clinical manifestations, and progression of disease. Understanding these differences is critical for age-specific diagnosis, management, and prevention of complications **(American Diabetes Association, 2026; Mayer-Davis et al., 2023).**

3.1 Pathophysiology in Children and Adolescents

Type 1 Diabetes (T1DM):

- **Autoimmune β-cell destruction:** T1DM is predominantly an autoimmune disorder in which the body's immune system targets and destroys insulin-producing pancreatic β-cells. This autoimmune process is mediated by autoreactive T lymphocytes, autoantibodies (such as GAD65, IA-2, and insulin autoantibodies), and environmental triggers, including viral infections or toxins **(Atkinson & Eisenbarth, 2020).**
- **Genetic predisposition:** Specific HLA genotypes, particularly HLA-DR3 and HLA-DR4, increase susceptibility to autoimmune β-cell destruction. Family history also plays a role in modulating disease risk.
- **Clinical progression:** Progressive β-cell loss leads to absolute insulin deficiency, resulting in hyperglycemia. The rapid onset of symptoms may culminate in **diabetic ketoacidosis (DKA)**, which is a life-threatening acute complication. DKA is characterized by dehydration, acidosis, electrolyte imbalances, and ketonemia.
- **Metabolic consequences:** Lack of insulin leads to increased gluconeogenesis, lipolysis, and ketogenesis. This contributes to the characteristic hyperglycemia and ketosis observed in T1DM.

Type 2 Diabetes (T2DM) in Youth:

- **Insulin resistance and β-cell dysfunction:** In adolescents, T2DM arises from a combination of peripheral insulin resistance (especially in skeletal muscle and liver) and relative insulin deficiency. Obesity, particularly central adiposity, exacerbates insulin resistance by releasing pro-inflammatory cytokines (e.g., TNF-α, IL-6) and free fatty acids that interfere with insulin signaling.

- **Compensatory mechanisms:** Initially, pancreatic β-cells increase insulin secretion to maintain euglycemia. Over time, chronic hyperglycemia and glucotoxicity impair β-cell function, leading to overt hyperglycemia **(Mayer-Davis et al., 2023).**
- **Clinical challenges:** Hyperglycemia develops gradually and may remain asymptomatic for months or years. Early detection is often incidental during routine health screenings.

Other Forms of Diabetes:

- **Maturity-Onset Diabetes of the Young (MODY):** A monogenic form caused by single-gene mutations affecting β-cell function. Autosomal dominant inheritance is typical, and clinical presentation can mimic T1DM or T2DM.
- **Secondary Diabetes:** Results from conditions such as cystic fibrosis, chronic pancreatitis, endocrine disorders (Cushing's syndrome, acromegaly), or medications like corticosteroids or antipsychotics.

3.2 Pathophysiology in the Elderly

Diabetes in elderly populations is predominantly T2DM, arising from a combination of insulin resistance, impaired insulin secretion, and age-related metabolic changes.

Insulin Resistance:

- Age-related reduction in skeletal muscle glucose uptake and impaired hepatic glucose suppression lead to chronic hyperglycemia.
- Increased visceral adiposity and chronic low-grade inflammation (inflammaging) contribute to insulin resistance.
- Cytokines such as TNF-α and IL-6, elevated in visceral fat, impair insulin signaling and exacerbate hyperglycemia **(Sinclair et al., 2021).**

β-cell Dysfunction:

- Pancreatic β-cell capacity declines with age due to both functional impairment and reduced β-cell mass.

- Chronic exposure to hyperglycemia, oxidative stress, and lipotoxicity further deteriorates insulin secretion.

Contributing Factors:

- Polypharmacy and comorbidities, including hypertension, cardiovascular disease, chronic kidney disease, and cognitive decline, influence glucose regulation.
- Decreased physical activity and reduced lean muscle mass (sarcopenia) impair glucose utilization.

Clinical Implications:

- Onset is often gradual and insidious, leading to delayed diagnosis.
- Elderly patients may exhibit atypical or nonspecific symptoms, such as recurrent infections, cognitive impairment, fatigue, or mild polyuria.
- Hypoglycemia risk is increased due to medications (insulin, sulfonylureas) and impaired counter-regulatory responses.

Key point: In elderly patients, age-related insulin resistance and β-cell decline, compounded by comorbidities and polypharmacy, define the pathophysiology and complicate management strategies.

3.3 Comparison Between Age Groups

Feature	Children/Adolescents	Elderly	Comments
Predominant Type	T1DM > T2DM	T2DM	Children mostly autoimmune; elderly mostly insulin resistance
Insulin Secretion	Absent (T1DM) / Reduced (T2DM)	Reduced	Decline in β-cell function with age in elderly
Insulin Resistance	Mild (T1DM) / Moderate (T2DM)	High	Obesity and inflammation drive resistance in both, more severe in elderly
Onset	Rapid (T1DM) / Gradual	Gradual	Acute in children T1DM,

	(T2DM)		chronic in elderly T2DM
Risk of Acute Complications	DKA common	HHS possible, hypoglycemia risk	Children present with ketoacidosis; elderly with hyperosmolar states
Contributing Factors	Autoimmune, genetics, lifestyle	Aging, comorbidities, medications	Genetic predisposition and lifestyle dominate in youth; aging-related metabolic changes dominate in elderly
Detection Challenges	Often symptomatic, but T2DM may be silent	Often asymptomatic, delayed diagnosis	Screening is crucial in both populations

Expanded Commentary:

- **Children/Adolescents:** Autoimmune destruction of β-cells is rapid in T1DM, leading to early metabolic derangements. T2DM develops slowly but is increasingly significant due to the obesity epidemic. Early intervention can prevent acute metabolic crises and long-term complications.
- **Elderly:** Hyperglycemia develops gradually, often masked by comorbidities or cognitive changes. Risk of both hyperglycemic emergencies (HHS) and hypoglycemia is high, making individualized monitoring and therapy essential.

4. Clinical Presentation of Diabetes in Children, Adolescents, and Elderly

The clinical presentation of diabetes varies according to age, type of diabetes, and duration of hyperglycemia. Recognizing age-specific signs and symptoms is critical for early diagnosis and timely intervention.

4.1 Clinical Presentation in Children and Adolescents

Type 1 Diabetes (T1DM):

- Usually presents acutely.
- **Common Symptoms:**

- Polyuria (frequent urination)
- Polydipsia (increased thirst)
- Polyphagia (increased hunger)
- Unexplained weight loss
- Fatigue and irritability

- **Acute Complications:**
  - Diabetic ketoacidosis (DKA) may be the initial presentation in up to 30–40% of cases in some populations **(Atkinson & Eisenbarth, 2020).**
  - DKA symptoms include vomiting, abdominal pain, rapid breathing (Kussmaul respirations), and altered consciousness.

Type 2 Diabetes (T2DM):

- Often develops gradually and may be asymptomatic initially.
- **Common Symptoms:**
  - Obesity and acanthosis nigricans (hyperpigmentation in skin folds)
  - Fatigue and mild polyuria or polydipsia
  - Recurrent infections (urinary tract, skin)
- Family history and lifestyle factors are important clues for early screening **(Mayer-Davis et al., 2023).**

Other Forms:

- MODY and secondary diabetes may present with mild hyperglycemia, and clinical features often depend on the underlying cause.

4.2 Clinical Presentation in the Elderly

Type 2 Diabetes (T2DM):

- The onset is usually slow and symptoms are often nonspecific.
- **Common Symptoms:**
  - Fatigue, lethargy, and weakness

- Polyuria and polydipsia may be less pronounced
- Blurred vision
- Recurrent infections and poor wound healing
- Cognitive impairment and mood changes in some cases **(Sinclair et al., 2021)**

Acute Complications:

- Hyperosmolar hyperglycemic state (HHS) may be the first presentation, especially in patients with severe dehydration or comorbid illness.
- Hypoglycemia is a significant concern in elderly patients, particularly those on insulin or sulfonylureas.

Chronic Complications:

- Elderly patients are at higher risk for both microvascular (retinopathy, nephropathy, neuropathy) and macrovascular complications (myocardial infarction, stroke) due to long-standing hyperglycemia and comorbidities **(Sinclair et al., 2021).**

4.3 Comparison Table: Clinical Presentation by Age

Feature	**Children/Adolescents**	**Elderly**
Onset	Rapid (T1DM) / Gradual (T2DM)	Gradual (T2DM)
Common Symptoms	Polyuria, polydipsia, weight loss	Fatigue, lethargy, mild polyuria
Acute Complications	DKA common	HHS possible, hypoglycemia risk
Chronic Complications	Rare initially	Higher risk due to comorbidities
Additional Signs	Acanthosis nigricans (T2DM)	Cognitive impairment, infections

Key Points

- Children/adolescents with T1DM often present acutely with DKA, while T2DM may be asymptomatic.
- Elderly patients often have nonspecific symptoms, and hyperglycemia may remain undiagnosed for long periods.

- Age-specific recognition of symptoms is essential for timely diagnosis and prevention of complications.

5. Diagnosis of Diabetes in Children, Adolescents, and Elderly

Early and accurate diagnosis is crucial for effective management of diabetes and prevention of complications. Diagnostic criteria are similar across age groups, but interpretation requires consideration of age-specific factors.

5.1 Diagnostic Criteria (ADA 2026)

Diagnosis of diabetes is confirmed by any **one** of the following:

- Fasting Plasma Glucose (FPG) ≥126 mg/dL (7.0 mmol/L) after at least 8 hours of fasting.
- 2-hour Plasma Glucose ≥200 mg/dL (11.1 mmol/L) during an Oral Glucose Tolerance Test (OGTT) using 75 g of glucose.
- HbA1c ≥6.5% (48 mmol/mol).
- Random Plasma Glucose ≥200 mg/dL (11.1 mmol/L) in the presence of classic symptoms of hyperglycemia or hyperglycemic crisis.

5.2 Age-Specific Considerations

Children and Adolescents:

- T1DM often presents with symptomatic hyperglycemia or diabetic ketoacidosis, requiring urgent blood glucose and ketone evaluation.
- T2DM may be asymptomatic; OGTT is recommended in high-risk children (obesity, family history, acanthosis nigricans) **(Mayer-Davis et al., 2023).**

Elderly:

- HbA1c may underestimate hyperglycemia in conditions like anemia or renal impairment.
- Postprandial glucose measurements may be more informative than fasting glucose in frail older adults **(Sinclair et al., 2021).**
- Screening should consider comorbidities, polypharmacy, and cognitive function.

6. Complications of Diabetes in Children, Adolescents, and Elderly

Chronic hyperglycemia and delayed diagnosis can result in acute and long-term complications, which vary with age.

6.1 Children and Adolescents

Acute Complications:

- Diabetic Ketoacidosis (DKA): More common in T1DM, life-threatening if untreated.
- Hypoglycemia: Often due to insulin therapy errors or missed meals.

Chronic Complications:

- Usually appear after several years of disease:
    - Microvascular: Retinopathy, nephropathy, neuropathy
    - Macrovascular: Rare during childhood but may appear in long-standing cases

6.2 Elderly

Acute Complications:

- Hyperosmolar Hyperglycemic State (HHS): More common in elderly with T2DM and dehydration.
- Hypoglycemia: Increased risk due to polypharmacy, renal impairment, and frailty.

Chronic Complications:

- Microvascular: Retinopathy, nephropathy, neuropathy
- Macrovascular: Myocardial infarction, stroke, peripheral vascular disease
- Cognitive decline and frailty may exacerbate complications and reduce quality of life **(Sinclair et al., 2021).**

8. Prevention Strategies in Children, Adolescents, and Elderly

Prevention of diabetes and its complications is a critical aspect of care, particularly in high-risk populations. Age-specific interventions can significantly reduce the incidence and severity of diabetes.

8.1 Children and Adolescents

Primary Prevention:

- **Lifestyle Modification:**
  - Encourage balanced diet rich in fruits, vegetables, and whole grains; reduce sugary and processed foods.
  - Promote regular physical activity, at least 60 minutes per day of moderate-to-vigorous exercise.
- **Weight Management:**
  - Maintain healthy BMI to reduce insulin resistance and risk of T2DM.
- **Education and Awareness:**
  - Family and school-based programs on healthy lifestyle choices and early recognition of symptoms.

Secondary Prevention:

- Screening children with obesity, family history of diabetes, or signs of insulin resistance (e.g., acanthosis nigricans) for early detection.
- Early management of prediabetes can delay or prevent progression to diabetes **(Mayer-Davis et al., 2023).**

8.2 Elderly

Lifestyle Measures:

- Maintain a balanced diet with controlled carbohydrate intake.
- Encourage moderate physical activity adapted to mobility and health status.

Medical Interventions:

- Monitor blood glucose regularly in high-risk individuals.
- Manage comorbidities such as hypertension, dyslipidemia, and obesity, which increase diabetes risk.
- Prevent polypharmacy where possible to reduce risk of hypoglycemia.

Screening:

- Regular screening for diabetes and prediabetes, particularly in individuals with risk factors such as family history, obesity, or cardiovascular disease **(Sinclair et al., 2021).**

10. Recent Advances and Future Directions in Diabetes Management

The management of diabetes in children, adolescents, and the elderly has evolved significantly due to technological innovations, pharmacological advances, and improved understanding of disease pathophysiology.

10.1 Children and Adolescents

- **Continuous Glucose Monitoring (CGM):**
  - Real-time glucose monitoring improves glycemic control and reduces hypoglycemia risk.
- **Insulin Pump Therapy and Hybrid Closed-Loop Systems:**
  - Enables precise insulin delivery and better glycemic stability.
- **Early Lifestyle Interventions:**
  - Structured family-based programs on nutrition, physical activity, and behavior modification.
- **Research Directions:**
  - Immunotherapy for prevention of T1DM progression.
  - Gene-based therapies and β-cell regeneration approaches **(Atkinson & Eisenbarth, 2020).**

10.2 Elderly

- **Pharmacological Advances:**
  - Introduction of DPP-4 inhibitors, GLP-1 receptor agonists, and SGLT2 inhibitors with lower hypoglycemia risk and cardiovascular benefits.
- **Telemedicine and Mobile Health:**
  - Remote monitoring and education improve adherence and early recognition of complications.

- **Individualized Therapy:**
  - Personalized glycemic targets considering frailty, comorbidities, and cognitive function.
- **Research Directions:**
  - Development of geriatric-specific diabetes care guidelines.
  - Exploration of anti-inflammatory therapies to reduce insulin resistance and complications **(Sinclair et al., 2021).**

11. Conclusion

Diabetes mellitus in children, adolescents, and the elderly presents unique challenges in terms of pathophysiology, clinical presentation, and management.

- Children and Adolescents:
  - T1DM remains the predominant form, with T2DM rising due to lifestyle and obesity.
  - Early recognition, family education, and modern technologies like CGM and insulin pumps are crucial.
- Elderly:
  - T2DM predominates, often complicated by comorbidities, polypharmacy, and atypical presentations.
  - Management focuses on individualized glycemic targets, prevention of hypoglycemia, and maintaining quality of life.
- General Principles:
  - Age-specific strategies in diagnosis, management, and psychosocial support improve outcomes.
  - Prevention through lifestyle modification, education, and early intervention is essential across all age groups.
  - Emerging therapies, telemedicine, and research into disease-modifying treatments offer promising avenues for better long-term control and reduction of complications.

The future of diabetes care lies in **personalized medicine**, early intervention, and integration of technology with patient-centered care to reduce morbidity, mortality, and improve quality of life across all age groups.

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Diabetes And Mental Health

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Introduction

Diabetes has emerged as one of the most pressing global health challenges of the twenty-first century. Once considered a disease of affluence, it now affects populations across both developed and developing nations, cutting across socioeconomic boundaries. The condition is not merely a metabolic disorder characterized by elevated blood glucose; it is a complex, lifelong illness that profoundly influences physical, psychological, and social well-being. Research consistently demonstrates that individuals living with type 1 or type 2 diabetes are more vulnerable to mental health difficulties, including depression, anxiety, and eating disorders. This vulnerability is not coincidental but arises from the demanding nature of diabetes management, the biological effects of chronic hyperglycaemia, and the emotional burden of living with a condition that requires constant vigilance. The interplay between diabetes and mental health is therefore bidirectional: poor psychological health undermines adherence to treatment, while inadequate diabetes control exacerbates psychological distress. Historically, the medical understanding of diabetes has evolved considerably. In 1815, glucose was first identified in the urine of a diabetic patient, and subsequent discoveries revealed its storage in the body as glycogen. Today, however, the challenge is not simply scientific discovery but the alarming rise in prevalence due to sedentary lifestyles, unhealthy diets, and increasing stress levels. Modern society has inadvertently created an environment conducive to diabetes, and with it, a surge in associated mental health problems.

Mental health, defined as emotional, psychological, and social well-being, plays a crucial role in shaping how individuals think, make decisions, and cope with life's challenges. A healthy mental state enables people to lead balanced, productive, and satisfying lives. Conversely, poor mental health diminishes resilience, reduces motivation, and impairs self-care. In the context of diabetes, this means that untreated depression or anxiety can directly compromise disease management, leading to poor glycemic control and increased risk of complications. Therefore, diabetes should not be viewed solely as a physical illness. It is a demanding chronic condition that affects both individuals and their families, requiring continuous adaptation and resilience. The psychological burden of diabetes — often referred to as “diabetes distress” — encompasses the negative emotions and stress associated with self-management. Patients may struggle with psychological insulin resistance, fear of hypoglycemia, or the stigma of living with a chronic illness. These challenges highlight the need for integrated care approaches that address both physical and mental health. In sum, diabetes represents a dual burden: a metabolic disorder with profound psychological implications. Recognizing and addressing this bidirectional relationship is essential for improving outcomes and enhancing quality of life. This study seeks to explore the intricate connections between diabetes and mental health, identify major psychological problems associated with the disease, and suggest strategies for integrated care.

Need and Importance of the Study

In the present era, diabetes has become a serious public health issue. The increasing number of cases has placed a significant burden on healthcare systems. Generally, treatment focuses on the physical aspects of the disease, while its psychological impacts are often overlooked.

Fear of complications affects the mental stability of individuals. Many patients remain anxious about the future and develop a sense of insecurity, which reduces their quality of life.

Conversely, mental health plays a crucial role in diabetes management. Individuals experiencing stress or depression may neglect medication, diet, and exercise, leading to poor glycemic control and increased complications.

Thus, a bidirectional relationship exists between diabetes and mental health, where both influence each other. Sudden lifestyle changes require individuals to make multiple self-directed decisions, making this study highly relevant and significant.

Objectives of the Study

- To understand the relationship between diabetes and mental health.
- To identify major psychological problems associated with diabetes.
- To examine the impact of mental health on diabetes management.
- To suggest effective strategies for integrated care and management.

Types of Diabetes

Diabetes is not a single disease but rather a group of metabolic disorders that share the common feature of chronic hyperglycaemia. Elevated blood sugar levels arise either because the body fails to produce insulin or because the cells cannot effectively utilize the insulin that is available. Understanding the different types of diabetes is essential, as each form has unique biological mechanisms, clinical presentations, and psychosocial implications.

Type 1 Diabetes

An autoimmune disorder in which the immune system destroys insulin-producing cells. Patients require lifelong insulin therapy. It is commonly seen in children and young individuals.

Type 2 Diabetes

Type 2 diabetes is the most prevalent form, accounting for the majority of cases worldwide. Unlike type 1, it is not primarily autoimmune but is characterized by insulin resistance — the body's cells fail to respond properly to insulin. Over time, the pancreas may also produce less insulin, compounding the problem. Type 2 diabetes is strongly associated with lifestyle factors such as poor diet, obesity, and physical inactivity, though genetic predisposition also plays a role. It typically develops in adulthood, but alarmingly, increasing numbers of children and adolescents are being diagnosed due to rising obesity rates. The management of type 2 diabetes often requires significant lifestyle changes, including dietary adjustments, regular exercise, and medication.

3. Gestational Diabetes

Occurs during pregnancy and usually resolves after childbirth, but increases the risk of developing Type 2 diabetes later.

Causes of Diabetes

Diabetes develops through a mix of genetic and lifestyle influences. A family history of the condition can predispose someone to it, but environmental and behavioral factors often play a decisive role. Consuming a diet high in processed foods and sugar, coupled with obesity and physical inactivity, significantly increases risk. Mental stress also contributes, as it can disrupt hormonal balance and impair the body's ability to regulate blood sugar effectively. Hormonal imbalances, such as those involving insulin or cortisol, further complicate glucose metabolism, making diabetes more likely to occur.

- Genetic factors
- Unhealthy diet
- Obesity
- Physical inactivity
- Mental stress
- Hormonal imbalance

The symptoms of diabetes often emerge gradually but can be quite disruptive. Frequent urination and excessive thirst are classic signs, reflecting the body's attempt to flush out excess glucose. Increased hunger, despite eating regularly, occurs because cells are unable to absorb glucose efficiently. Sudden weight loss may follow, as the body begins breaking down fat and muscle for energy. Fatigue and weakness are common, stemming from poor energy utilization. Slow wound healing and blurred vision highlight the systemic impact of high blood sugar, affecting circulation and nerve function. Recognizing these symptoms early is crucial, as timely intervention can prevent complications and improve quality of life.

Symptoms

- Frequent urination
- Excessive thirst
- Increased hunger
- Sudden weight loss
- Fatigue and weakness
- Slow wound healing
- Blurred vision

Diabetes not only affects physical health but also has profound psychological consequences. Beyond its established links with mental illness, the condition often triggers specific emotional challenges that directly influence blood sugar regulation. Stress, anxiety, and diabetes-related distress can undermine self-care routines, making it harder to maintain stable glucose levels.

This cycle increases the likelihood of complications, future disability, and even premature mortality if the disease remains uncontrolled.

The physical toll of unmanaged diabetes is extensive. Cardiovascular diseases are among the most serious outcomes, as high blood sugar damages blood vessels and raises the risk of heart attacks and strokes. The kidneys, which filter waste from the blood, can also be impaired, leading to chronic kidney disease. Vision problems, particularly diabetic retinopathy, occur when fragile blood vessels in the eyes are damaged, potentially causing blindness. Nerve damage, or neuropathy, is another common complication, often resulting in pain, numbness, or loss of sensation in the extremities. Additionally, elevated glucose levels weaken the immune system, leaving individuals more vulnerable to infections. Together, these effects highlight why diabetes must be managed holistically—addressing both physical and psychological aspects to reduce complications and preserve quality of life

Diabetes is diagnosed through several key tests that measure how the body manages blood sugar. The **Fasting Blood Sugar Test** is often the first step, taken after an overnight fast to check baseline glucose levels. Elevated results may indicate impaired regulation. The **Postprandial (PP) Test** measures blood sugar two hours after eating, revealing how effectively the body processes glucose from food. Another important tool is the **HbA1c Test**, which reflects average blood sugar levels over the past two to three months by assessing glycated hemoglobin. This test is particularly useful for monitoring long-term control and treatment effectiveness. Finally, the **Oral Glucose Tolerance Test (OGTT)** provides a more detailed picture by tracking blood sugar before and after consuming a glucose-rich drink, helping to identify prediabetes and diabetes with precision.

Together, these diagnostic methods give healthcare providers a comprehensive view of a patient's glucose metabolism. Early detection through these tests is vital, as it allows timely intervention to prevent complications. By combining immediate measures like fasting and post-meal glucose with long-term indicators such as HbA1c, doctors can tailor treatment plans more effectively, ensuring better management and reducing the risk of serious health outcomes.

Treatment and Management

Diabetes cannot be completely cured but can be effectively managed:

- Balanced diet (low sugar, low fat)
- Regular exercise (at least 30 minutes daily)

- Medication or insulin as prescribed
- Regular monitoring of blood glucose
- Stress management through yoga and meditation
- Preventing diabetes requires a proactive approach that blends healthy habits with mindful living. At the core of prevention is adopting a **balanced lifestyle**. Choosing a diet rich in whole grains, fresh fruits, vegetables, lean proteins, and healthy fats helps regulate blood sugar and reduces the risk of insulin resistance. Limiting processed foods and sugary drinks is equally important, as they contribute to weight gain and poor metabolic health.
- **Regular physical activity** plays a vital role in prevention. Engaging in exercises such as walking, cycling, or yoga improves insulin sensitivity, supports cardiovascular health, and helps maintain a healthy weight. Weight management is another critical factor, since excess body fat—especially around the abdomen—can increase the likelihood of developing type 2 diabetes.
- Equally significant is **stress reduction**. Chronic stress can disrupt hormonal balance, elevate cortisol levels, and impair glucose regulation. Techniques like meditation, deep breathing, or even pursuing hobbies can help manage stress effectively.
- Together, these strategies form a holistic shield against diabetes. By combining nutritious eating, consistent exercise, weight control, and emotional well-being, individuals can significantly lower their risk, enhance overall health, and build resilience against future complications. Prevention is not just about avoiding disease—it's about cultivating a healthier, more sustainable lifestyle
- Diabetes, when left uncontrolled, can gradually damage multiple systems in the body, leading to a wide range of physical complications. Persistent high blood sugar, known as hyperglycaemia, places continuous strain on blood vessels and organs. Over time, this increases the risk of **cardiovascular diseases**, including heart attacks and strokes. The kidneys are particularly vulnerable, with many patients developing **nephropathy**, which can progress to chronic kidney disease. The eyes are also affected, as fragile blood vessels in the retina may be damaged, resulting in **retinopathy** and potential vision loss.
- Another serious consequence is neuropathy, or nerve damage, which often causes pain, numbness, or loss of sensation in the hands and feet. This can lead to diabetic foot

complications, where minor injuries fail to heal properly, sometimes resulting in severe infections. Elevated glucose levels also weaken the immune system, making individuals more prone to infections. Beyond these, patients often experience fatigue and weakness, as their bodies struggle to use energy efficiently. Digestive issues such as gastroparesis may occur when nerve damage slows stomach emptying. Diabetes can also contribute to sexual dysfunction and various skin disorders, reflecting its widespread impact.

- Importantly, the burden of diabetes is not only physical. A cross-sectional study in India found that about 36% of diabetic patients showed symptoms of depression, underscoring the deep connection between physical complications and mental health challenges. Together, these effects highlight why strict glucose control and holistic care are essential to prevent disability and improve quality of life.

Mental Problems Caused by Diabetes,

Living with diabetes often brings a heavy psychological burden alongside its physical complications. One of the most common mental health challenges is **depression**, which manifests as persistent sadness, hopelessness, and loss of interest in daily life. This emotional state not only undermines self-esteem but also reduces motivation to follow treatment plans, making blood sugar control more difficult and increasing the risk of complications. **Anxiety** is another frequent issue. Many patients live in constant worry about disease progression, potential complications, or sudden changes in glucose levels. This ongoing apprehension can lead to sleep disturbances, irritability, and poor concentration, further eroding quality of life. Closely related is **diabetes distress**, a condition unique to those managing diabetes. The daily demands of strict diet, regular exercise, medication schedules, and continuous monitoring often feel overwhelming, leading to frustration, emotional exhaustion, and a sense of helplessness. Fear also plays a significant role. Some individuals develop needle phobia, making insulin injections daunting, while others fear hypoglycaemic episodes due to their sudden and severe symptoms. These fears can drive maladaptive behaviours such as overeating or avoiding insulin therapy, complicating disease management. Beyond personal struggles, **social isolation and stigma** add to the psychological toll. Patients may hesitate to disclose their condition, limiting social support and increasing loneliness. Financial pressures from lifelong treatment further intensify stress. Eating disorders—including anorexia, bulimia, and binge eating—are also more common among people with diabetes than in the general population, highlighting the complex interplay between mental and physical health.

Altogether, these challenges show that diabetes is not only a medical condition but also a psychological one. Addressing both aspects is essential for effective management and for improving overall well-being.The relationship between mental health and diabetes is deeply interconnected. Poor psychological well-being often leads to **non-adherence to treatment**, which directly worsens glycaemic control. When individuals struggle with depression, anxiety, or emotional distress, they may neglect medication schedules, dietary restrictions, or regular monitoring of blood sugar. This lack of consistency increases the risk of immediate complications and contributes to long-term health problems such as cardiovascular disease, kidney damage, and neuropathy. In contrast, good mental health fosters motivation, discipline, and resilience, enabling patients to follow treatment plans more effectively and achieve better outcomes. People living with both type 1 and type 2 diabetes are at a significantly higher risk of developing depression, anxiety, and eating disorders compared to the general population. These conditions interfere with daily management routines, creating a cycle where poor mental health worsens diabetes, and uncontrolled diabetes further aggravates psychological distress.

The impact is especially pronounced in special groups. For children, the challenge lies in accepting the condition and adapting to lifestyle changes at a young age. Women often face additional complications due to hormonal fluctuations, which can affect both mood and glucose regulation. Elderly patients may struggle with loneliness, reduced social support, and multiple comorbidities, making management even more complex.

Studies highlight the bidirectional nature of this relationship: stress and depression not only result from diabetes but can also increase the risk of developing the condition in the first place. This underscores the importance of integrated care that addresses both physical and psychological needs. Supporting mental health is not just about improving emotional well-being—it is a critical step toward effective diabetes management and reducing the burden of complications.

Management of Mental Health

- Psychological counselling and therapy
- Antidepressants/anti-anxiety medications (if required)
- Healthy lifestyle practices
- Yoga, meditation, pranayama

- Social support from family and friends

Diabetes is one of the most common chronic conditions worldwide, and its prevention requires a holistic approach that considers both physical and mental health. Because diabetes often overlaps with mental illness, clinicians must be aware of the psychological state of their patients. Supporting individuals in improving their mental health and coping strategies can reduce stress, enhance adherence to lifestyle changes, and lower the risk of complications. While Type 1 diabetes cannot be prevented, Type 2 diabetes is largely avoidable through consistent lifestyle management.

- A **balanced, fiber-rich diet** is the cornerstone of prevention. Whole grains, fresh fruits, vegetables, and lean proteins help regulate blood sugar and improve insulin sensitivity. Avoiding processed foods, sugary drinks, and excessive fats reduces the risk of obesity, a major contributor to diabetes. Alongside diet, **regular exercise**—such as walking, cycling, or yoga—strengthens the cardiovascular system, aids weight control, and enhances glucose metabolism.
- Maintaining a healthy weight is critical, as excess body fat, particularly around the abdomen, increases insulin resistance. Equally important is **adequate sleep**, since poor sleep patterns disrupt hormonal balance and impair glucose regulation. **Stress management** through meditation, relaxation techniques, or hobbies helps reduce cortisol levels, which otherwise interfere with blood sugar control. Avoiding harmful habits like **smoking and alcohol consumption** further protects metabolic health.
- Finally, regular health check-ups allow for early detection of prediabetes and timely intervention. By combining physical care with psychological support, individuals can significantly reduce their risk of developing diabetes and its complications. Prevention is not simply about avoiding disease—it is about cultivating resilience, balance, and long-term well-being.
- The evidence strongly demonstrates that diabetes and mental health are deeply intertwined, forming a complex and bidirectional relationship. Diabetes should not be regarded solely as a physical illness, because its impact extends far beyond blood sugar regulation. It influences emotional stability, social interactions, and overall quality of life. Patients often face continuous psychological stress, anxiety, and depression, which not only diminish well-being but also reduce adherence to treatment regimens. In turn,

poor mental health worsens glycaemic control, creating a vicious cycle of declining physical and psychological health.

Breaking this cycle requires more than medical intervention alone. Social support, awareness, and education play a vital role in empowering individuals to manage both the physical and emotional demands of diabetes. A holistic approach that integrates medical care with psychological and social support is essential for improving outcomes.

Scientific research further highlights the biological mechanisms underlying this connection. Insulin resistance and chronic hyperglycaemia disrupt neurotransmitter balance, affecting mood and cognition. Activation of the hypothalamic-pituitary-adrenal (HPA) axis elevates cortisol levels, which interfere with insulin effectiveness. Long-term hyperglycaemia contributes to neuronal damage, while stress activates the sympathetic nervous system, further impairing glucose regulation. These pathways illustrate that the relationship between diabetes and mental health is not only behavioural but also rooted in neuroendocrine processes.

Incorporating mental health care into diabetes management can therefore significantly improve both disease control and overall quality of life. Addressing psychological distress, reducing stigma, and promoting coping strategies are as important as medication and lifestyle changes. Ultimately, treating diabetes as a condition that spans physical, emotional, and social dimensions offers the best chance of reducing complications and enhancing long-term well-being.

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Digital Health Ecosystems: Integrating Diabetes Care with Broader Chronic Disease Management

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ABSTRACT

Chronic illnesses such as diabetes are highly prevalent, multimorbid, and the cost of health care has been rising, which has a huge burden worldwide. The potential of digital health ecosystems as interconnected networks of mobile applications, wearables, continuous glucose monitoring (CGM), artificial intelligence (AI), telehealth, electronic health records (EHRs) and interoperability standards such as FHIR includes a transformative potential regarding shifting siloed, reactive care to proactive, integrated, patient-centred care. The chapter explains the manner in which these technological ecosystems have emerged, especially in diabetes-specific inventions like Continuous Glucose Monitoring (CGM), AI-assisted hypoglycemia prediction, and mHealth apps. More so, it describes how the solutions can be applied to comorbidity management, such as managing hypertension, chronic kidney disease, cardiovascular disease, and mental health disorders. Evidence of the situation can be found in the real-world applications, like the NHS App in the UK, Teladoc/Livongo in the US, and mobile-first in India and Africa, which improve glycemic control (lower HbA1c), reduce hospitalisations, improve quality of life, and manage multimorbidity. Such challenges as data privacy (GDPR/HIPAA), cybersecurity, and digital divides, bias in AI, and regulatory barriers are discussed critically and responded to with solutions such as the hybrid models, policy changes, and inclusive design. New technologies, such as IoT/IoMT, education-based virtual reality, the integration of genomics, security based on blockchain, and digital twins, offer specificity and prevention. Finally, the digital ecosystems make diabetes a pivotal point in holistic chronic care in a seamless way, enabling equitable and sustainable health systems in a personalised manner.

Keywords: Digital health ecosystems, Diabetes care, Chronic disease management, Multimorbidity, Interoperability, Artificial intelligence, Continuous glucose monitoring, Patient-centred care

INTRODUCTION

Non-communicable diseases (NCDs), or chronic diseases, constitute one of the most important health issues of the 21st century on the global level. These conditions, which persist for one year or more, require ongoing medical attention and often limit daily activities, account for the majority of deaths and disabilities worldwide (World Health Organisation, 2025). Recent estimates have identified that about 75 per cent of people worldwide die because of NCDs, with premature mortality caused by cardiovascular disease, cancer, chronic respiratory diseases, and diabetes increasing because of factors such as population ageing, urbanisation and lifestyle changes (World Health Organisation, 2025). The financial impact is truly overwhelming, as it is projected that chronic illnesses may cost the world economy as much as 47 trillion by 2030 unless the trends are reversed (Bauer et al., 2023). The presence of multiple morbidities, i.e. the presence of 2 or more chronic conditions, is becoming more frequent, and it is putting a strain on healthcare systems and lowering the quality of life of millions of people.

Diabetes is one of the best examples of a growing crisis among chronic diseases. By 2024, it is estimated that 589 million adults aged between 20 and 79 years were living with diabetes across the world, and this figure was about 11.1 per cent (or 1 in 9) of the number of adults in this age group (International Diabetes Federation, 2025). It is estimated that this population will increase exponentially to 853 million by 2050 due to changes in demographics, urbanisation, and other risk factors like obesity and lack of physical activity (International Diabetes Federation, 2025).

This implies that diabetes poses a serious risk, and this risk is aggravated by the fact that a significant portion of the population has the disease without their knowledge (it has been estimated that more than 40 per cent of patients remain undiagnosed) (International Diabetes Federation, 2025). The illness has a significant financial burden, and the worldwide spending on healthcare costs related to diabetes amounted to over a trillion dollars over the last few years (International Diabetes Federation, 2025).

The most important feature of the burden of diabetes is its deep correlation with comorbidities, which increases the risks and makes it more difficult to manage. The most notable one is cardiovascular disease (CVD), since patients with diabetes have a high risk of heart disease, stroke, and similar incidents. Hypertension is a significant prevalence among diabetic patients and tends to co-exist based on similar pathophysiological processes such as insulin resistance and endothelial dysfunction. These risks are worsened by obesity, which is a leading cause of type 2 diabetes; research has found that an elevated body mass index (BMI), waist circumference and waist-to-height ratio are closely related to the increase in hypertension-diabetes comorbidity (Wang et al., 2023). As an example, obesity significantly increases the ratio of risk factors in the development of both hypertension and diabetes, and central obesity imposes extra uncorrelated risks (Wang et al., 2023). These interrelations result in a vicious cycle of exacerbation of each condition by the others and subsequent polypharmacy, increased hospitalisation and inferior outcomes.

Digital health technologies provide a way forward in these interrelated challenges, as they can transform healthcare to be less fragmented, less siloed, and more integrated and ecosystem-oriented. Conventional care has been typified with a lot of isolation in terms of treating illnesses, little information flow between the provider and the patients due to the rare face-to-face contacts. Digital health describes the utilisation of technologies to monitor and communicate data in real-time and offer interventions that are tailored with the utilisation of such technologies, including mobile applications, wearables, electronic health records (EHRs), telemedicine, and artificial intelligence (AI) (Shaw et al., 2023). This change will help with the proactive, patient-centred administration, especially in chronic cases where self-management and early diagnosis are paramount. Remote patient monitoring, predictive analytics to anticipate complications, and coordinated multidisciplinary team-based care become more efficient, predictable, and adherent through digital platforms (Shaw et al., 2023).

Significance of the Chapter

This chapter is important since it looks at the possibility of digital health ecosystems to connect diabetes care with the larger management of chronic disease, multi-infected NCDs, in the context of increasing interconnectedness. Such ecosystems have the potential to decrease fragmentation, improve preventive measures, and decrease the overall impact on healthcare systems due to the combination of diabetes-specific instruments (e.g., continuous glucose monitoring) and the management of comorbid conditions (such as CVD and hypertension). In view of the accelerated pace of technology adoption and other long-term issues, such as inequality in access, it is important to learn the models of integration to achieve fair and sustainable development in global health.

Chapter Objectives

The main objectives of this chapter are to: (a) discuss the models of how diabetes-specific digital interventions may be integrated into larger chronic disease ecosystems; (b) discuss the benefits, i.e. better clinical outcomes, patient empowerment, and cost efficiencies; (c) discuss the main challenges, i.e. interoperability, privacy issues, and digital divides; (d) discuss the future implications, i.e. innovations are emerging, e.g., predictive care driven by AI, and policy suggestions on how to scale the proposed ideas into practice.

Scope and Definitions

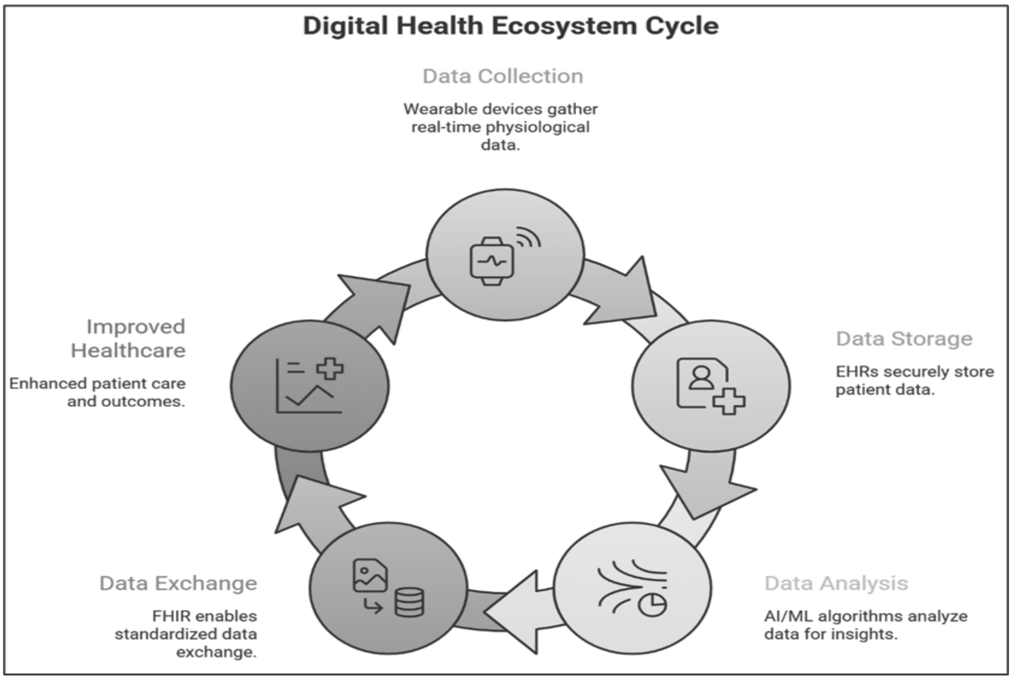
This chapter is about digital health ecosystems with chronic disease management as its primary prism through which the concept of diabetes is examined, but also multimorbid conditions. A digital health ecosystem describes networked systems that include applications, wearables, electronic health records, artificial intelligence algorithms, telehealth applications, and information-sharing structures that allow the free flow of information and collaborative care and health assistance (Gray et al., 2023). The treatment of diabetes includes clinical care (e.g., glucose levels), treatment (e.g., insulin, lifestyle modification), and prevention (e.g., prediabetes risk reduction). The broader chronic disease management is a more comprehensive and integrated way to deal with multimorbid patients, in which multiple conditions should be managed together with coordinated and data-driven strategies, as opposed to silo-based disease management (Gray et al., 2023).

UNDERSTANDING DIGITAL HEALTH ECOSYSTEMS

Digital health ecosystems are interrelated systems of technologies that allow the data on health to be collected, shared, analysed, and used in a seamless way to achieve comprehensive care delivery. These ecosystems combine various elements to form a unified setting to handle health matters, especially chronic conditions (Gray et al., 2023).

Elements of Digital Health Ecosystems

Data platforms, devices, advanced analytics, and connectivity standards are all key elements of Digital Health Ecosystems. Cloud-based electronic health records (EHRs) are centralised databases that can store patient information securely, and they can be accessed to retrieve and track clinical information longitudinally across providers (Shaw et al., 2024). Smartwatches and continuous glucose monitors (CGMs) are wearable gadgets that show real-time physiological activity information, including glucose levels, heart rate, movement, and rest, enabling remote physiological monitoring and abnormalities identification (Huang et al., 2025). The algorithms of artificial intelligence (AI) and machine learning (ML) analyse large amounts of data and produce insights, including a model of risk prediction of complications or an automated decision-support system (Gray et al., 2023). The standardised data exchange through APIs, supported by interoperability standards, especially Fast Healthcare Interoperability Resources (FHIR) by HL7, allows the disparate systems (e.g., wearables, EHRs, and apps) to communicate successfully and safely (Lehne et al., 2019; HL7 international, n.d.). FHIR facilitates structured observations, medication and care plan resources, which encourage cross-ecosystem integration (InterSystems, n.d.).



The diagram below illustrates the digital health ecosystem cycle (Figure 1).

Transformation of Traditional to Digital Models

Traditional healthcare systems were characterised by fragmentation and provider-centricity, which included the use of paper records, periodic face-to-face interactions, and a small amount of data sharing across silos. The care is reactive and aimed more at acute events than at prevention; the patients were often passive recipients with minimal coordination between specialists (McGinnis et al., 2021). The digital transformation creates a new form of integrated ecosystems with patient-centred care as a primary consideration. Patients can self-manage and make shared decisions that are powered by digital transformation through uninterrupted access to their data through portals and apps (Shaw et al., 2024). The given evolution highlights the active, holistic models in which data moves both ways between patients, providers, and devices, decreasing the number of areas of fragmentation and enhancing continuity across the caring environments (Gray et al., 2023). Telehealth and remote monitoring technologies are just some technologies that have extended care beyond clinical walls, which promotes empowerment and engagement (Huang et al., 2025).

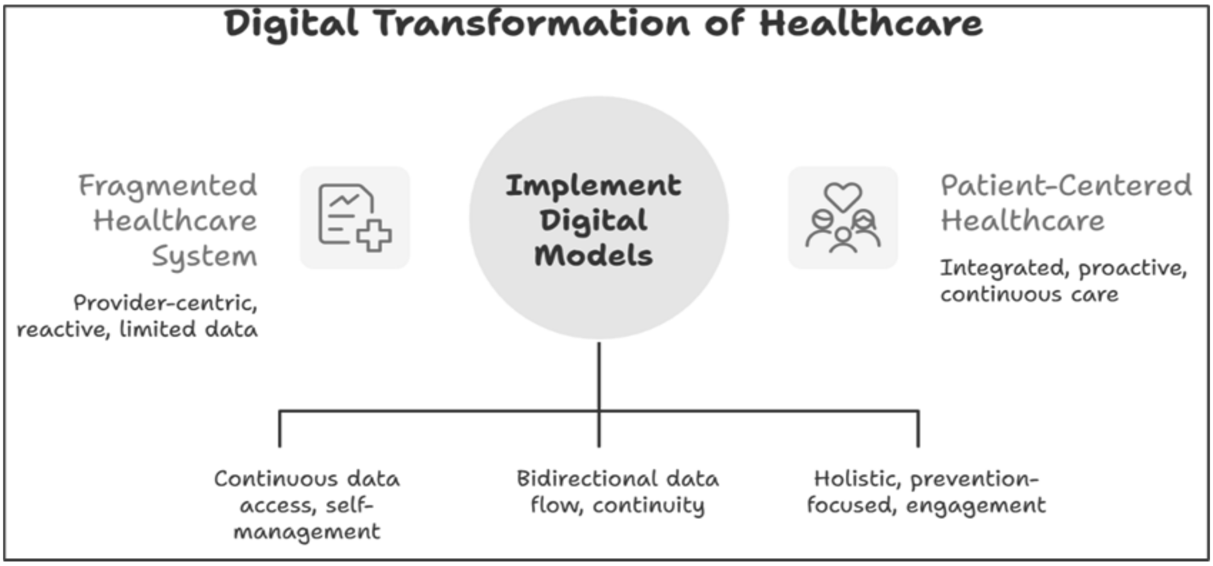


Figure 2 DIGITAL TRANSFORMATION OF HEALTHCARE

Roles in Chronic disease management.

The digital health ecosystem has become a vital part of managing chronic diseases and enables the sharing of data, as well as the development of personalised interventions. Wearables and EHRs integration allows sharing real-time data and may provide a complete view of patient conditions to reduce the information gap (Gray et al., 2023). The AI/ML is fueled by predictive analytics to identify the trends and predict risks, such as hypoglycemic episodes in diabetes or heart failure attacks, and ensure that preventive actions can be taken beforehand (Shaw et al., 2024). Individual recommendations lead to specific interventions, including individual treatment programmes based on the combination of glucose, blood pressure, and lifestyle data, which increase adherence and outcomes (Huang et al., 2025). The capabilities assist in dealing with multimorbidity as they collaborate to provide holistic care, value-based care, decrease hospitalisations, and enhance the quality of life (Gray et al., 2023).

To conclude, digital health ecosystems revolutionise chronic care by turning it into proactive and integrated, as well as patient-empowered, using interconnected pieces and parts to achieve better results.

DIABETES CARE IN THE DIGITAL AGE

The management of diabetes has completely changed during the era of digitalisation as a set of new tools enables patients to gain more control over their level of Glycemic control, improve their self-management, and minimise complications. These innovations transition the management to a proactive and data-driven management style (Shaw et al., 2024).

Existing Digital Aids in Diabetes.

Modern digital platforms in diabetes are mobile applications, wearable devices, and telehealth platforms. Applications on the smartphone can be used to calculate the insulin dosage, count of carbohydrates, and meal, exercise, and medication log; among them are mySugr, One Drop, and Glooko, which can combine data to provide individualised insights and share with the provider (ADCES, n.d.; OpenLoop Health, 2024). Glucose notifications and trend monitoring are offered through wearables, especially smartwatches and special sensors; most of them can be connected to apps and provide real-time notifications about highs or lows (Huang et al., 2025). Telehealth solutions support virtual care, remote care and multidisciplinary care and therefore allow making timely changes without the need to visit the doctor (HHS Telehealth, 2024). These tools tend to be connected to electronic health records or cloud systems to have a smooth data flow (Shaw et al., 2024)

Data-Driven Diabetes Management

Continuous glucose monitoring (CGM) is the main component of data-driven care, which is real-time interstitial glucose measurements at intervals of several minutes with subcutaneous sensors, which eliminate regular fingersticks and give trends, alerts, and time-in-range indicators (TIR;

70-180 mg/dL) (International Diabetes Federation, 2025). Advanced CGM systems, which support predictive features, include real-time, intermittently scanned systems. Machine learning and artificial intelligence (AI) enhance the authority of hypoglycemia based on the tendencies that have been identified previously in historical information of glucose, physical activity, and food intake, which anticipate low events hours in advance and engage preventive actions, including carbohydrate uptake or insulin dosage (Kodama et al., 2023; Gray et al., 2023). Mobile health (mHealth) promotes patient attendance by offering applications assisting to remind, deliver educational knowledge, gamification, and behaviour coaching, which form compliance with monitoring, diet, and exercise (Shaw et al., 2024).

Outcomes and Evidence

There is strong evidence that digital interventions can enhance important clinical and patient-centred outcomes. Various studies and meta-analyses indicate that there are major reductions in HbA1c. As an example, CGM implementation in diabetes type 1 and type 2 results in a reduction of HbA1c of 0.24%-0.7% or greater, and more benefits when used regularly (>75% of days) and higher base level (>8.5%) (JAMA Network Open, 2025; Shaw et al., 2024). Hospitalisations (up to 67% in certain studies) and emergency visits (40%), in turn, are associated with reduced hospitalisations and emergency visits, which can be explained by more effective prevention of acute events (JMCP, 2024). There is an increase in the quality of life due to a decrease in diabetes distress, self-efficacy, and satisfaction with managing the condition; mHealth interventions increase participation and promote the overall well-being (Gray et al., 2023). Although the benefits are more evident among people who become engaged users, its long-term adoption is essential to achieve long-term benefits (International Diabetes Federation, 2025).

All these tools bring diabetes care to precision and empowerment, and there are still inequitable access and integration issues.

BROADER CHRONIC DISEASE MANAGEMENT: BEYOND DIABETES

Circuitry chronic disease management goes beyond mono-condition management, which recognises the inter-relationships of multimorbidities that are frequent with diabetes. It is based on the idea of holistic interventions in order to treat co-occurring conditions to achieve greater success through digital ecosystems (Gray et al., 2023).

Comorbidities of Diabetes

Diabetes is often comorbid with other chronic conditions, which increases the health risks due to common pathophysiological mechanisms. One of the primary comorbidities is hypertension, with insulin resistance and vascular inflammation contributing to the development of hypertension in up to 73% of type 2 diabetes patients at the time of diagnosis (McFarlane et al., 2022). Another serious association is chronic kidney disease (CKD), for which diabetes is the cause of nearly half of the cases with end-stage renal disease; depression in diabetic patients increases the risk of CKD by 2030 per cent (Novak et al., 2016). The rates of mental health disorders, including anxiety and depression, are doubled in diabetic communities, amplifying cardiovascular outcomes and mortality in a bidirectional manner of poor adherence and hyperglycemia due to stress (Chireh & D'Arcy, 2022). Systemic inflammation and obesity overlap increase the odds of respiratory problems, such as chronic obstructive pulmonary disease (COPD), asthma; in such cases, comorbid respiratory diseases are associated with a higher incidence of diabetes in lifestyle risk factors (Lee et al., 2019). They are comorbidities that form a network where each condition exacerbates the others, causing faster disease progression and shorter life expectancy (Forbes & Cooper, 2023).

Multimorbidity Digital Tools

Multimorbidity Digital health ecosystems provide multimorbid conditions with versatile applications that cohesively integrate data across diseases to manage these conditions. Such tools as wearable sensors to measure heart failure and monitor indicators of fluid status, heart rate variability, and activity allow intervening early to prevent exacerbations in the patient with comorbid diabetes (Costello et al., 2021). Mental health Chatbots based on AI offer cognitive behavioural therapy (CBT) sessions, mood monitoring, and crisis intervention based on natural language processing, which is especially useful among depressed or anxious diabetic patients (Fiske et al., 2022). Such tools as smart home systems will integrate AI and the IoT to monitor older adults with chronic diseases in a holistic way, predicting frailty or multimorbidity (Castro et al., 2022). In the case of respiratory comorbidities, adaptive AI is used to control digital home monitoring to adapt asthma or COPD management, combining pulmonary data with the diabetes glucose trends to issue joint alerts (Costello et al., 2023). They can be used to engage patients in a gamified application and virtual coaching, treating comorbidities such as hypertension and CKD through predictive analytics (Vega et al., 2025).

Holistic vs. Disease-Specific Approaches

Disease-specific approaches are effective in isolated conditions, although they fail in multimorbidity to enhance siloed care, which ignores interaction, resulting in polypharmacy, or a sequence of five or more medications (Srivastava, 2024). Holistic models, on the other hand, combine lifestyle pillars of medicine (nutrition, exercise, stress management) with medical care, targeting underlying causes. Deprescribing and behavioural interventions can also reduce polypharmacy in chronic patients by 1520 per cent (Guthrie et al., 2015). Guideline reviews lead to evidence-based approaches aimed at modifying condition-specific guidelines into multimorbidity models, focusing on patient-centred guidelines that reduce lifestyle risk factors such as sedentary behaviour and poor diet that cause diabetes-comorbid clusters (Kraemer et al., 2019). Holistic-based integrated care is effective because it helps to decrease hospital readmissions, promote transdisciplinary collaboration, and improve the quality of life in polypharmacy-prone elderly with multiple chronics (Carlson & Yarns, 2023). The shift to holistic paradigms is a crucial change towards sustainable management because the concept can address the factors of polypharmacy and lifestyle holistically, as well as preventative treatment instead of a reactive one (Muth et al., 2018).

Essentially, the inclusion of multimorbidity in the care of diabetes (digital, holistic) is more likely to bring more equitable and effective chronic management.

STRATEGIES FOR INTEGRATION

Interoperability and Data Integration

Health digital ecosystems must achieve effective integration through solid interoperability to facilitate effective, secure, cross-disease and platform data exchange. Such standards as Fast Healthcare Interoperability Resources (FHIR) by HL7 have been at the centre of this initiative and offer modern APIs to structured data sharing that can help manage chronic diseases (Lehne et al., 2019; HL7 International, n.d.). FHIR supports reliable information between electronic health records (EHRs), wearables, and apps, eliminating silos and allowing a full view of multimorbid patients (Gray et al., 2023). FHIR-based application programming interfaces (APIs) enable access to clinical data in real-time, including the glucose levels, blood pressure or level of renal functionality. These are complemented by blockchain technology providing decentralised and immutable data exchange ledgers to ensure integrity, patient consent management, and anti-tampering, especially of critical chronic conditions data among providers (Yue et al., 2016; Agbo et al., 2019). Raising privacy, Blockchain-based cryptographic hashing and smart contracts contribute to complying with laws, such as HIPAA, and support collaborative care in a situation with multimorbidity (Hathaliya and Tanwar, 2020).

Patient-Centric Design

Patient-centric design focuses on usability interfaces where various chronic conditions are integrated into a single dashboard to enable individuals have an overall healthcare perspective. Such dashboards combine both diabetes data (e.g., CGM data, HbA1C trends) and comorbid conditions (e.g., hypertension, CKD, or mental health indicators), and present them in a visual format to be easily interpreted and followed in terms of trends (Doyle et al., 2021). It has such features as self-tailored alerts, self-management educational resources based on multimorbidity, and goal-setting tools (Gray et al., 2023). This is made possible by user-centred approaches that consider co-design with patients, guarantee accessibility, reduced cognitive load, and relevance, e.g., including lifestyle considerations and social determinants to gain the necessary insights (Shaw et al., 2024). Single-purpose platforms help to enhance interaction with the provision of actionable summaries that support adherence and active decision-making in complex care plans.

Provider and System-Level Integration

Provider and system-level integration entails the collaboration of multidisciplinary teams through shared care plans with the support of digital ecosystems. They include endocrinologists, cardiologists, nephrologists, pharmacists, and behavioural specialists who have interoperable platforms (with) coordinated planning, real-time updates, and virtual consultations (HealthManagement.org, 2024). Available in EHR-linked tools, shared care plans describe objectives, roles, and monitoring goals, responsibilities, and progress across conditions to reduce the risks of fragmentation and polypharmacy (Muth et al., 2018). Technology companies (i. e., app developers, AI vendors) and health systems can collaborate to advance new concepts in ecosystems; such efforts are already undertaken through scalable remote health monitoring and data-driven protocols, e.g. in efforts promoting interoperability frameworks (CMS, 2025). Alliances of this nature enable smooth adoption, training, and retention of chronic care.

AI and Predictive Analytics

There is no better solution than AI and Predictive Analytics Machine learning (ML) aiding the incorporation of diabetes data and other chronic indicators to the next level of risk stratification. Predictive models compute the multimodal inputs, which include EHRs, wearables, genomics, and lifestyle data, to predict the complications in diabetic patients, such as cardiovascular events, CKD progression, or mental health exacerbations (Vega et al., 2025). The highest accuracy of gradient boosting or deep learning techniques is to predict high-risk clusters and provide early interventions and individual management (Kodama et al., 2023). The AI helps to provide the overall risk points by connecting the glucose fluctuations with the measurements linked to hypertension or obesity, which enhances the outcomes with the ability to provide warning signs and specific treatments (Shaw et al., 2024). These functions change the care towards prevention when there are multiple morbidities.

In brief, the combination of leveraging standards, patient-centred tools, collaborative models, and artificial intelligence results in consistent ecosystems of diabetes care with chronic care management, addressing the needs of each patient fairly and effectively.

CASE STUDIES AND REAL WORLD APPLICATIONS

Effective Implementations

A number of live implementations show the power of digital health ecosystems to integrate diabetes care into the greater chronic disease management. The NHS App is a notable example of national-level platforms in the United Kingdom that contribute to the integrated management of diabetes and hypertension. The app, which was launched as the digital front door to the NHS, allows a user to get test results (including the HbA1c when it comes to diabetes or blood pressure measurements), order repeat prescriptions, appointments, and health records (NHS England, 2025a). In HbA1c graphs, systolic/diastolic blood pressure charts, and chronic condition management tools (such as diabetes) with personalised recommendations and monitoring have recently been added (NHS App release notes, 2025). Although this is mainly targeted at primary care integration, the app can support self- management in multimorbid patients by uniting data and enhancing remote communication, which will help to achieve a higher level of engagement and continuity (Greenhalgh et al., 2024). Assessments indicate that it minimises fragmentation, although complete integration of multimorbidity requires local GP record add-ons.

A successful example of a commercial multimorbidity management platform in the United States is **Livongo (since acquired by Teladoc Health)**. Developed by an original diabetes orientation including correlated glucose metre, coaching, and real-time insights, Livongo was developed further as an integrated chronic care after being acquired by Teladoc. Research indicates that any form of treating various conditions (e.g., diabetes and hypertension) through the same platform is better compared to single-condition programmes. As an example, integrated users had consistent improvements in HbA1c levels, systolic blood pressure (i.e., clinically significant changes after 412 weeks), and weight, and even greater benefits when they received mental health support (i.e., an extra 0.5% HbA1c, 9.6 mmHg blood pressure reduction, etc.) (Teladoc Health, 2022). The improvements in the HbA1C of 0.8-1.6 per cent were verified in cohorts of diabetics in randomised trials, and the engagement and satisfaction rate is excellent (PMC7995078, 2021). The results highlight the importance of whole-person care, and AI nudges and coaching can increase adherence to comorbidities.

Global Perspectives Approaches differ greatly between the high-income countries (HICs) and low- and middle-income countries (LMICs) on the basis of their resource availability, infrastructure, and priorities. Implementations in HICs such as the UK or the US, including the NHS App and Teladoc/Livongo, utilise the power of advanced interoperability, EHR integration and ubiquitous access to smartphones to create comprehensive data-rich ecosystems to support diabetes (and hypertension, mental health, and other chronics) (Shaw et al., 2024).

Mobile-first ecosystems prevail in LMICs with much mobile penetration and a lack of traditional infrastructure. MHealth programmes such as **mDiabetes** (Arogya World) also provide SMS-based diabetes education to millions of people in India, where 15% cumulative changes in diabetes risk behaviours have been achieved through lifestyle messaging (Frontiers in Public Health, 2024). The apps like BeatO and mySugr allow monitoring the glucose level, doctor visits, and individualised instructions, whereas the national system, like eSanjeevani telemedicine, helps manage diabetes in rural areas (TechSci Research, 2025). Ayushman Bharat Digital Mission enhances chronic care interoperability and unified health IDs (PMC8606976, 2021). The mobile-first approaches put more emphasis on prevention and awareness in resource-intensive environments, and often target type 2 diabetes related to lifestyle.

MHealth approaches to diabetes management have potential in Africa, and systematic reviews reveal that mHealth interventions for diabetes reduce HbA1c levels significantly due to SMS reminders, education, and monitors (PLOS Digital Health, 2025). The self-management, promoted by mobile apps, is in sub-Saharan Africa, where the prevalence of diabetes increases with the lack of access to healthcare (PMC11978007, 2025). Such examples are telephone-based education that strengthens self-management to control blood pressure in diabetic elderly people.

These strategies focus on cost and scale through simple mobile capabilities, which are opposed to HIC's dependence on wearables and AI, but have issues such as connectedness and literacy.

Lessons Learned

Successful implementations reflect important enablers/ barriers. Scalability can be effective when the platforms are compatible with the current systems (e.g., the integration of NHS with GP records) and the feedback provided by patients during scaling (Gray et al., 2023). It leads to high engagement because of personalisation, including AI nudges in Teladoc/Livongo and SMS convenience in LMICs (Teladoc Health, 2022; Arogya World studies). Combined strategies are better than disjointed ones, which lower HbA1c and comorbidities.

The obstacles to adoption are: digital divides (e.g. access inequities in LMICs), privacy, technical failure, and preference for face-to-face care (Shaw et al., 2024). Fragmentation and a lack of incentive in HICs and low awareness, dual entry, and infrastructure barriers in LMICs are hindrances to full adoption and reach, respectively (PMC11752663, 2024). The barriers are overcome by focusing on stakeholder collaboration, training, clarity of regulations, and inclusion in design (Muth et al., 2018). Co-design, long-term involvement, and non-linear models are more sustainable, whereas equity can be used to broaden the reach in various situations.

These examples demonstrate how digital ecosystems can be used to transform the system, but emphasise how it is necessary to implement context-specific changes to realise equitable and scalable chronic disease integration.

CHALLENGES AND SOLUTIONS

Technical Barriers Digital health ecosystems face a considerable threat of technical barriers that prevent the smooth integration and efficient functioning in chronic disease management. The most significant issue is data privacy, and it has to be in compliance with such regulations as the General Data Protection Regulation (GDPR) in Europe or the Health Insurance Portability and Accountability Act (HIPAA) in the United States. These rules require a safe management of sensitive health data, such as consent to the sharing, transmission, and storage of data, but breaches and interoperability issues tend to reveal the vulnerabilities (Shaw et al., 2024). Cybersecurity risks are on the increase, and healthcare systems have become a subject of ransomware and unauthorised access, which can take down patient data and disrupt care delivery (National Academy of Medicine, 2022). These obstacles to integration are attributed to the inefficiency of the legacy systems to be integrated with the modern tools, leading to the fragmentation of the data flow, suboptimal usage, and the technical breakdown in the example of multimorbidity (Gray et al., 2023).

Equity and Access Problems

Digital divide has been used to increase the gaps in management of chronic diseases, particularly among the underserved groups and people of advanced age. Low income, low education, and rural residence are also related to low access to high-speed internet, smartphones or gadgets required to use such tools as continuous glucose monitoring or telehealth (PMC11662839, 2024). Some other barriers that older adults face are lower levels of digital literacy, cognitive impairment, and preference for face-to-face care, which further complicates the disparities in self-rated health and chronic condition outcomes (JAMA Network Open, 2025). Under-servicing and regular exclusion of racial minorities and groups with low resources may increase the degree of health inequity in diabetes and comorbidities (PMC11705165, 2024).

Control and Ethical Issues

The issue of regulation and ethics is also problematic issue for digital health tools. The U.S. Food and Drug Administration (FDA) prioritises the safety, effectiveness, and post-market surveillance of the products in question, and thus, the AI-enabled devices cannot be easily approved to be used as a medical device because the rate of their actions may be slow compared to the rate of innovation (FDA, 2025). The problem of AI bias arises when they are trained using a biased dataset, which recreates inequalities in diagnosis or prediction of risks in underrepresented populations (PMC8963864, 2022). The ethical application of data requires disclosure, informed consent, accountability, and elimination of algorithmic discrimination to support such principles as justice and non-maleficence (PMC12076083, 2025).

Overcoming Obstacles

Solutions need multifaceted solutions to progress adoption. The policy changes must encourage interoperability requirements (e.g., FHIR), and equitable access with subsidies of devices and broadband, as well as clear regulatory pathways for AI tools (WHO, 2020). Digital literacy, confidence, and integration skills, including co-design to improve usability, can be developed through the application of training programs to healthcare providers and patients (Shaw et al., 2024). Hybrid models merging digital technologies with face-to-face care will accommodate the needs and technical restrictions to ensure continuity to the users with low connectivity or the elderly without losing interest (PMC10568450, 2023). Inclusive and sustainable ecosystems are also supported by user-centred design, promotion by communities, and continuous bias and privacy monitoring (Gray et al., 2023).

By responding to these difficulties using evidence-based strategies that are collaborative, digital health ecosystems will have the capability of supporting integrated chronic care fairly.

FUTURE TRENDS AND TECHNOLOGIES

Emerging Technologies

The future of the digital health ecosystem will be determined by transformational technologies that will improve integration, personalisation, and security in chronic disease management. Continuous and real-time monitoring with interconnected wearables, sensors, and smart implants to monitor glucose, blood pressure, cardiac activity, and other parameters to provide proactive chronic care, e.g., in diabetes and heart failure, is made possible by the **Internet of Things (IoT)** and particularly, the Internet of Medical Things **(IoMT)** (Charter Global, 2025; BCG, 2025). The **Virtual Reality (VR)** and **Augmented reality (AR)** have already led to educational and therapeutic advances in patient education and treatment, as well as providing patients with immersive experiences to manage diabetes independently, count carbohydrates, prevent hypoglycemia by putting them in a simulated condition, reducing stress through mindfulness classes, and teaching therapeutic education with high knowledge retention (PMC11571515, 2025; MDPI, 2025). These are tools that simplify difficult concepts and make them more interesting to follow up on, and enhance compliance among children and adults.

The integration of genomics is a step toward precision medicine, which is the combination of genetic information (e.g., polygenic risk score, pharmacogenomics) and digital programmes to prevent and cure diabetes and comorbidities such as cardiovascular disease (PMC12839427, 2025; Zoho, 2025). Digital twins are virtual copies that run on AI and multi-omics data to show the personal health pathway of people to insulin dosage, complications, and smart care-related adjustments (ScienceDirect, 2025). People can use **blockchain** to enforce secure ecosystems that ensure privacy, interoperability, and tamper-proof records across providers and facilitate consent management and compliance in multimorbidity environments through decentralised, immaterial logs to share data (PMC12860446, 2025; Paubox, 2025).

Policy and Research Recommendations

To achieve this potential, special policies and research are needed. The future research must give preference to long-term engagement, adaptive low-burden, and rigorous validation of the multimodal platforms to multimorbidity, including equity-based trials of different population groups (PMC12803440, 2025). Sustainability and reduction of environmental impact should be funded by scalable pilots using the combination of IoMT, genomics, and AI, as well as conducting life-cycle analysis (MDPI, 2025). Global partnerships help to standardise (e.g., FHIR extensions to support genomics), bridge digital divides, and establish international processes of ethical AI and data governance, developing on WHO approaches (WHO, 2020). The policymakers ought to encourage the reimbursement of VR education tools, blockchain-secured platforms, and hybrid models and the trade of workforce in digital literacy.

Vision for Integrated Care

Envision a wholly integrated digital health system in which diabetes is the entry point to effective management of all chronic diseases. Patients have a single patient-centric interface that collects real-time IoMT, genomic information, lifestyle and predictive AI to provide personalised and proactive intervention, preventing hypertension, CKD and mental disease complications and others. Blockchain guarantees secure and interoperable data streams, whereas VR/AR gives the power to education and changing behaviour. Care providers also work through dynamic, shared care plans in which they transition to value-based care that is preventive in nature. This holistic paradigm enables individuals, minimises the burden of the systems, and enhances just and sustainable health in the ageing populations across the globe.

CONCLUSION

Digital health ecosystem integration is a paradigm shift in chronic disease management, and diabetes is an ideal lead point to holistic, interconnected care. In the course of this chapter, we have discussed how those ecosystems, which operate on interoperable platforms, wearables, AI-based analytics, telehealth, and patient-centric tools, go beyond the traditional disease-specific silo of multiforbidity.

Key Takeaways

Digital health ecosystems have transformative potential in regard to integrating diabetes care in the context of chronic disease management. They allow sharing of data across states of being -

connecting glucose measurements and hypertension, cardiovascular risk, chronic kidney disease, mental health, and lifestyle-related factors with the help of such standards as FHIR, secure blockchain technology, and cloud computing. A variety of clinical outcomes are improved through continuous glucose monitoring, predictive AI on hypoglycemia, complication prediction, remote heart failure, and personalised mHealth, which represented improvements in HbA1c, reduced hospitalisation, enhanced time-in-range and improved quality of life (Shaw et al., 2024; Gray et al., 2023). The examples of the NHS App and built-in dashboards (UK), whole-person chronic care (Teladoc/Livongo), and mobile-first (India and Africa) can help demonstrate that scalable, context-adapted ecosystems can minimise fragmentation, empower patients, and assist in the work of multidisciplinary teams. However, even though the issues of data privacy, cybersecurity, digital divides, regulatory lag, and AI bias persist, according to the evidence, integrated digital strategies are much more successful than isolated models, especially with multimorbid patients at risk of polypharmacy and overlapping risk factors (Vega et al., 2025; Muth et al., 2018).

Call to Action

It takes intentional, cooperative action by the entire stakeholder group to make all the promises of these ecosystems. Clinicians need to accept the presence of digital tools in their everyday practice, promote interoperability in their organisations, and collaborate in the creation of patient-centred solutions that are seamlessly integrated into workflows. The priorities of policymakers and health system administrators must include equal access funding, strong interoperability standards, less burdensome regulatory access to AI and digital therapeutics, and incentive reimbursement in preventive and integrated care. The technology makers and industry collaborators have a role to play in establishing a more inclusive and bias-conscious platform, excellent cybersecurity, and collaborating with healthcare systems to bridge the digital divide by providing affordable devices, offline functionality, and culturally sensitive design. Combined, these stakeholders should bridge the gap in technical, regulatory, and equity to enable integrated digital chronic care to be accessible and sustainable to every population.

Final Thoughts

The advent of digital health ecosystems is a sign that the direction of medicine is shifting towards a completely new path of preventive, patient-centred, and personalised medicine. With real-time data, predictive analytics, and recreational connectivity, healthcare will not be reactive when it comes to treating individual ailments but proactive when it comes to the overall individual. Diabetes has already established impressive digital capabilities and strong links to most comorbid conditions, and it has a bright future as the entry point to this future, where the risk-anticipating, the customising-intervention, and the lifelong health supporting platform bring the chronic ailments together. In addition to providing better clinical outcomes and system load reductions, this change not only restores agency in the patients but also promotes equity and brings care to the advanced complexity of living with multimorbidity as a lifetime concern. Long-term commitment, innovation and collaboration will be needed to make this vision a reality, but the foundation has been set, and the possibility of transforming the lives of millions is close.

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Role of Public Health Nutrition in the Prevention and Management of Diabetes: A 360° Perspective

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Abstract

Diabetes mellitus has emerged as a major global public health challenge, driven by rapid urbanization, lifestyle transitions, and nutritional imbalances. Public health nutrition plays a pivotal role in both the prevention and management of diabetes by addressing dietary risk factors at population and individual levels. This chapter presents a 360° perspective on how integrated nutritional strategies can reduce disease burden and improve health outcomes. From a preventive standpoint, public health nutrition emphasizes balanced diets rich in whole grains, fruits, vegetables, and micronutrients while limiting refined sugars, trans fats, and ultra-processed foods. Community-based interventions, nutrition education, and behavior change communication are critical in promoting healthy eating patterns and reducing obesity a key risk factor for type 2 diabetes. Policy-level measures, including food labeling, taxation on sugary beverages, and fortification programs, further support healthier food environments. In diabetes management, medical nutrition therapy (MNT) forms a cornerstone, focusing on glycemic control, weight management, and prevention of complications. Tailored dietary planning, culturally appropriate meal patterns, and continuous monitoring enhance patient adherence and long-term outcomes. Public health nutrition also integrates multidisciplinary approaches involving healthcare systems, schools, workplaces, and community platforms to ensure sustained impact. A 360° approach underscores the synergy between science, society, and self-care, highlighting the importance of evidence-based interventions, supportive policies, and individual responsibility. Strengthening public health nutrition frameworks can significantly contribute to reducing diabetes prevalence, improving quality of life, and achieving sustainable health goals globally.

Keywords: Public Health Nutrition, Diabetes Mellitus, Lifestyle Diseases, Micronutrients, Preventive Nutrition, Food Policy, Community Health, Self-care

1. Introduction

Diabetes mellitus has emerged as one of the most significant global public health challenges of the 21st century, affecting millions of people across diverse populations worldwide. According to the International Diabetes Federation, the global prevalence of diabetes is increasing at an alarming rate, with a substantial proportion of cases remaining undiagnosed (International Diabetes Federation, 2021). Low- and middle-income countries bear a disproportionate share of this burden, largely due to rapid urbanization, dietary transitions, and sedentary lifestyles that intensify risk factors (IDF, 2021; World Health Organization, 2022). India, often referred to as the "diabetes capital of the world," is experiencing a sharp rise in both type 1 and type 2 diabetes cases, driven by demographic and lifestyle changes. This escalating burden in India represents not only a major public health issue but also a socio-economic challenge, as it predominantly affects individuals in their productive years and leads to increased healthcare expenditures and reduced workforce productivity (Anjana et al., 2023; IDF, 2021).

A critical factor contributing to the rising burden of diabetes is the ongoing nutrition transition, characterized by a shift from traditional diets to energy-dense, nutrient-poor food patterns. This transition involves increased consumption of refined carbohydrates, saturated fats, added sugars, and ultra-processed foods, coupled with declining levels of physical activity, leading to a surge in obesity and metabolic disorders (Popkin, 2017; World Health Organization, 2022). Traditional Indian diets, once rich in whole grains, pulses, fruits, and vegetables, are increasingly being replaced by fast foods and sugar-sweetened beverages, particularly in urban settings (Misra et al., 2011; Popkin, 2017). This dietary shift, driven by globalization, urbanization, and evolving food environments, has played a significant role in the growing prevalence of diabetes and other non-communicable diseases (WHO, 2022; Popkin, 2017). The concept of public health nutrition has gained considerable importance in addressing the rising burden of diet-related diseases such as diabetes. Public health nutrition extends beyond individual dietary choices to encompass population-level strategies aimed at improving nutritional status and preventing disease. It integrates principles from nutrition science, epidemiology, health promotion, and policy-making to address the root causes of malnutrition and non-communicable diseases (World Health Organization, 2022; Beaglehole et al., 2011). Public health nutrition focuses on creating supportive food environments, promoting healthy behaviors through education and communication, and implementing policies such as food fortification, labeling, and fiscal measures to encourage healthier dietary practices (WHO, 2022; Hawkes et al., 2015). In the case of diabetes, public health nutrition plays a vital role in both prevention and management by targeting risk factors at community, institutional, and policy levels (WHO, 2022; International Diabetes Federation, 2021). Given the multifactorial nature of diabetes, there is a growing need for a 360° integrated approach that combines science, society, and self-care. The scientific dimension involves evidence-based research, technological advancements, and clinical interventions, including medical nutrition therapy and early diagnosis (IDF, 2021). The societal dimension emphasizes the role of communities, governments, and institutions in shaping food systems, ensuring food security, and promoting equitable access to healthy foods (Hawkes et al., 2015). Meanwhile, self-care highlights individual responsibility in adopting healthy dietary practices, maintaining physical activity, and adhering to treatment regimens (American Diabetes Association, 2022). Such an integrated approach recognizes that no single strategy can effectively address the complexity of diabetes. Instead, a synergistic model that aligns scientific knowledge with social support systems and individual behavior change is essential. This 360° perspective not only enhances prevention and management strategies but also contributes to sustainable health outcomes, ultimately reducing the burden of diabetes and improving quality of life at both individual and population levels (WHO, 2022; IDF, 2021).

2. Understanding Diabetes: A Public Health Perspective

Diabetes mellitus is a chronic metabolic disorder characterized by elevated blood glucose levels due to defects in insulin secretion, insulin action, or both. From a public health perspective, it is a multifactorial condition influenced by biological, behavioral, socio-economic, and environmental determinants. Its rapidly increasing global prevalence highlights the need for a comprehensive understanding of its types, risk factors, and broader determinants (International Diabetes Federation, 2021). Diabetes is broadly classified into three main types. Type 1 diabetes is an autoimmune condition resulting in absolute insulin deficiency and requires lifelong insulin therapy (American Diabetes Association, 2022). Type 2 diabetes, the most common form, is characterized by insulin resistance and is strongly associated with unhealthy diet, physical inactivity, and obesity (IDF, 2021; World Health Organization, 2022). Gestational diabetes occurs during pregnancy and increases the risk of complications and future diabetes in women (ADA, 2022). Diet and lifestyle are major contributors to diabetes risk. High intake of refined carbohydrates, sugars, and ultra-processed foods, along with low consumption of fruits, vegetables, and fiber, promotes obesity and insulin resistance (WHO, 2022). Sedentary behavior and urban lifestyles further exacerbate the risk. Additionally, genetic predisposition and family history increase susceptibility (Hu, 2011). Socio-economic and environmental factors also play a critical role. Poverty, limited access to nutritious food, and inadequate healthcare services increase disease burden, while urbanization and unhealthy food environments worsen lifestyle risks (Hill et al., 2013; Popkin, 2017). Social inequalities often result in delayed diagnosis and poor disease management. The rising prevalence of diabetes places a heavy burden on healthcare systems due to long-term care needs and complications (IDF, 2021). In low-resource settings, high treatment costs further strain families (Bommer et al., 2017). Therefore, a comprehensive public health approach focusing on prevention, early detection, and management is essential to reduce the burden and improve population health outcomes (Beaglehole et al., 2011; WHO, 2022).

3. Role of Nutrition in Diabetes Etiology

Nutrition plays a central role in the etiology of diabetes, particularly type 2 diabetes, by influencing metabolic pathways, insulin sensitivity, and overall energy balance. Dietary patterns characterized by poor-quality foods and nutrient imbalances significantly contribute to the onset and progression of the disease (World Health Organization, 2022; Hu, 2011). Understanding the relationship between specific dietary components and metabolic dysfunction is essential for effective prevention strategies. One of the major contributors to diabetes risk is the consumption of high glycemic diets and ultra-processed foods. Foods with a high glycemic index (GI), such as white bread, polished rice, and sugary snacks, cause rapid spikes in blood glucose levels, increasing insulin demand and eventually leading to insulin resistance (Jenkins et al., 2002; Augustin et al., 2015). Ultra-processed foods, rich in added sugars, unhealthy fats, and additives, further exacerbate metabolic stress and promote weight gain (Monteiro et al., 2019). Refined carbohydrates and added sugars play a particularly harmful role in diabetes etiology. Unlike complex carbohydrates, refined carbohydrates are rapidly digested and absorbed, leading to sudden increases in blood glucose and insulin levels. High consumption of sugar-sweetened beverages, desserts, and packaged foods contributes to chronic hyperglycemia and obesity, one of the strongest predictors of type 2 diabetes (Malik et al., 2010; WHO, 2022). Prolonged high sugar intake is also associated with pancreatic beta-cell dysfunction (Hu, 2011). The quality of dietary fats is another critical factor. Trans fats, commonly found in hydrogenated oils and fried foods, promote inflammation and insulin resistance while increasing cardiovascular risk

(Mozaffarian et al., 2006). In contrast, monounsaturated and polyunsaturated fats from nuts, seeds, fish, and vegetable oils improve insulin sensitivity and support metabolic health (Salas-Salvadó et al., 2011). Dietary fiber plays a protective role in diabetes prevention. Fiber-rich foods such as whole grains, legumes, fruits, and vegetables slow glucose absorption and improve glycemic control. Soluble fiber enhances insulin response and supports gut health, which is increasingly linked to metabolic regulation (Reynolds et al., 2019). Micronutrient deficiencies also contribute to impaired glucose metabolism. Trace elements such as zinc, magnesium, chromium, and iron are essential for insulin synthesis, secretion, and function. Magnesium deficiency is associated with increased insulin resistance, while chromium enhances insulin activity. Zinc supports insulin storage, and iron imbalance affects oxidative stress and pancreatic function (Barbagallo & Dominguez, 2015; WHO, 2022).

4. Public Health Nutrition Strategies for Diabetes Prevention

Effective prevention of diabetes requires a comprehensive public health nutrition approach that operates at multiple levels population, community, and policy. These strategies aim to address the root causes of unhealthy dietary behaviors while creating supportive environments that promote sustainable lifestyle changes.

4.1 Population-Based Approaches

Population-based strategies are vital for improving dietary patterns and reducing diabetes risk across communities. National dietary guidelines and food pyramids provide evidence-based recommendations, promoting the consumption of whole grains, fruits, vegetables, and healthy fats while limiting sugars, salt, and unhealthy fats (World Health Organization, 2022; Food and Agriculture Organization, 2019). These frameworks guide public health interventions aimed at encouraging healthier behaviors. School and workplace nutrition programs further support these efforts. School initiatives such as mid-day meals, nutrition education, and restrictions on junk food help establish healthy habits early in life (Story et al., 2009). Workplace wellness programs promote balanced diets, physical activity, and routine health screenings, reducing lifestyle-related risks (Anderson et al., 2009). Food labeling and awareness campaigns empower consumers to make informed choices. Front-of-pack labels and mass media campaigns improve awareness and encourage healthier dietary practices, contributing to diabetes prevention at the population level (Hawkes et al., 2015; WHO, 2022).

4.2 Community-Based Interventions

Community-level interventions are essential for translating nutrition strategies into practical action, particularly in rural and underserved areas. Nutrition education and counseling programs improve awareness about balanced diets, portion control, and glycemic management, thereby supporting diabetes prevention and control (World Health Organization, 2022; Food and Agriculture Organization, 2019). Tailoring these interventions to local food habits and cultural practices enhances their effectiveness (Contento, 2016).

Grassroots health workers such as ASHA and Anganwadi workers play a key role in promoting healthy behaviors, conducting awareness programs, and facilitating early detection of diabetes (Ministry of Health and Family Welfare, 2020). Additionally, promoting traditional diets and millets supports better glycemic control due to their high fiber and nutrient content (Anitha et al., 2021). Encouraging indigenous foods improves dietary diversity and contributes to sustainable and culturally appropriate nutrition practices (WHO, 2022).

4.3 Policy-Level Interventions

Policy-level actions are crucial in shaping food environments and influencing population behavior. Fiscal measures such as sugar taxes on sugar-sweetened beverages and regulations on ultra-processed foods help reduce their consumption and promote healthier alternatives (World Health Organization, 2022; Hawkes et al., 2015). These policies can also generate revenue for public health initiatives. Food fortification programs address micronutrient deficiencies by enriching staple foods with nutrients like iron and zinc, thereby improving overall nutritional status (Food and Agriculture Organization, 2019).

In India, national initiatives such as the National Programme for Prevention and Control of Cancer, Diabetes, Cardiovascular Diseases and Stroke (NPCDCS) and POSHAN Abhiyaan focus on promoting healthy lifestyles, improving nutrition, and strengthening early detection and management of non-communicable diseases (Ministry of Health and Family Welfare [MoHFW], 2020; NITI Aayog, 2021). These integrated efforts contribute significantly to reducing the burden of diabetes.

5. Role of Micronutrients in Diabetes Management

Micronutrients play a crucial yet often underappreciated role in diabetes management by influencing insulin function, glucose metabolism, and oxidative balance. Deficiencies or imbalances in essential trace elements can impair metabolic control and increase the risk of complications, highlighting the importance of adequate micronutrient intake in diabetes care (World Health Organization, 2022; Barbagallo & Dominguez, 2015). **Zinc (Zn)** is essential for insulin synthesis, storage, and secretion in pancreatic beta cells. It stabilizes insulin and exhibits antioxidant properties that protect against oxidative stress, a common feature in diabetes. Zinc deficiency may impair insulin function and glycemic control (Chausmer, 1998). Magnesium (Mg) plays a key role in glucose metabolism and insulin signaling, acting as a cofactor for enzymes involved in carbohydrate metabolism. Low magnesium levels are strongly associated with insulin resistance and poor glycemic control, while adequate intake improves insulin sensitivity (Barbagallo & Dominguez, 2015). **Chromium (Cr)** enhances insulin action by facilitating glucose uptake and improving carbohydrate and lipid metabolism. Its deficiency is linked to impaired glucose tolerance and increased insulin resistance (Vincent, 2000). Iron (Fe), although essential, has a dual role; excess iron contributes to oxidative stress and pancreatic beta-cell damage, increasing diabetes risk (Fernández-Real & Manco, 2014). Broader strategies such as biofortification and dietary diversification are vital for improving micronutrient intake. Biofortification enhances nutrient content in staple crops, while diversified diets rich in whole grains, pulses, fruits, vegetables, nuts, and seeds ensure balanced micronutrient intake (Food and Agriculture Organization, 2019).

6. Dietary Approaches for Diabetes Management

Dietary management is a cornerstone in the control and treatment of diabetes, playing a vital role in maintaining optimal blood glucose levels, preventing complications, and improving quality of life. Evidence-based dietary approaches emphasize the quality, quantity, and timing of food intake to support metabolic health (American Diabetes Association, 2022; World Health Organization, 2022). A low Glycemic Index (GI) diet is widely recommended for diabetes management. Low-GI foods such as whole grains, legumes, and non-starchy vegetables are digested slowly, resulting in gradual increases in blood glucose and improved glycemic control (Jenkins et al., 2002; Augustin et al., 2015). Replacing high-GI foods like refined cereals and sugary snacks with healthier alternatives is an effective strategy. Balanced macronutrient intake is equally important, with complex carbohydrates as the primary energy source, adequate protein for satiety and repair, and healthy fats improving insulin sensitivity and cardiovascular health (ADA, 2022). The inclusion of functional foods and nutraceuticals has gained attention for their potential benefits. Foods such as oats, barley, flaxseeds, fenugreek, and bitter gourd contain bioactive compounds that may support glycemic control (Reynolds et al., 2019). Fiber-rich diets, particularly those high in soluble fiber, slow glucose absorption, improve lipid profiles, and aid in weight management (WHO, 2022). Effective meal planning and portion control are critical for maintaining stable blood glucose levels. Structured meal patterns, carbohydrate counting, and tools like the plate method help individuals make informed dietary choices (ADA, 2022). Personalized meal plans tailored to cultural preferences and metabolic needs enhance adherence and long-term success.

7. Social and Cultural Dimensions of Nutrition

Nutrition is deeply embedded within social and cultural contexts, influencing dietary behaviors, food choices, and the risk and management of diseases such as diabetes. Understanding these dimensions is essential for designing culturally appropriate public health nutrition interventions (World Health Organization, 2022; Popkin, 2017). Food habits and cultural beliefs strongly shape dietary patterns. Traditional practices, religious norms, and local food availability determine eating behaviors. While many traditional diets are balanced and protective, certain customs such as frequent consumption of fried foods, refined carbohydrates, and sugary festival foods may increase diabetes risk (Misra et al., 2011). Misconceptions and limited awareness about healthy diets further influence food choices.

Urban rural differences in dietary patterns are also evident. Urban populations increasingly consume processed and convenience foods due to lifestyle changes and greater market access, leading to higher intake of energy-dense, nutrient-poor diets (Popkin, 2017). In contrast, rural diets have traditionally included whole grains and locally sourced foods, though these are gradually being replaced by packaged foods due to market penetration and changing aspirations (WHO, 2022). Marketing and globalization have significantly transformed food environments. Aggressive promotion of ultra-processed foods and sugary beverages, especially among youth, has increased their consumption. Western dietary patterns high in sugar, salt, and fat are increasingly replacing traditional diets (Hawkes et al., 2015). Gender and socio-economic disparities further affect nutrition. Women in low-income households often face limited access to nutritious foods, while economic constraints drive reliance on cheaper, unhealthy options, increasing diabetes risk (WHO, 2022). Addressing these social determinants is essential for effective diabetes prevention.

8. Role of Behavior Change and Self-Care

Behavior change and self-care are fundamental in the prevention and management of diabetes, as long-term outcomes depend largely on individual lifestyle practices and adherence to recommended interventions. Strengthening these aspects requires a combination of knowledge, motivation, and supportive environments (World Health Organization, 2022; American Diabetes Association, 2022). Nutrition literacy is a key driver of behavior change, enabling individuals to understand dietary information, interpret food labels, and make healthier choices. Improved literacy helps control portion sizes and reduce the intake of high-risk foods such as refined sugars and ultra-processed products (WHO, 2022; Contento, 2016). Public health education initiatives play a significant role in enhancing these skills. Lifestyle modification, including a balanced diet and regular physical activity, is essential for diabetes control. Low glycemic index diets and fiber-rich foods improve blood glucose regulation, while activities such as walking, yoga, and aerobic exercise enhance insulin sensitivity and support weight management (ADA, 2022; Colberg et al., 2016). Sustainable, long-term lifestyle changes are more effective than short-term interventions. Digital health tools have further strengthened self-care practices. Mobile apps, wearable devices, and telehealth platforms allow individuals to monitor glucose levels, track diet and activity, and access personalized guidance, improving adherence and outcomes (WHO, 2022).

Patient empowerment and adherence are central to effective management. When individuals are equipped with knowledge and supported by healthcare providers, family, and community systems, they are more likely to maintain healthy behaviors and achieve better glycemic control (ADA, 2022).

9. Challenges in Public Health Nutrition for Diabetes

Despite growing recognition of the role of nutrition in diabetes prevention and management, several challenges hinder the effective implementation of public health nutrition strategies. These barriers operate at individual, community, and policy levels, limiting the overall impact of interventions (World Health Organization, 2022; Food and Agriculture Organization, 2019). Food insecurity and affordability remain major challenges, particularly in low- and middle-income countries. Many populations lack consistent access to safe and nutritious foods, while healthier options such as fruits, vegetables, and whole grains are often more expensive than processed, energy-dense foods. This economic constraint leads disadvantaged groups to rely on cheaper, unhealthy diets, increasing their risk of obesity and diabetes (FAO, 2019; WHO, 2022).

Seasonal variations and supply chain issues further worsen access to nutritious foods. Lack of awareness about healthy dietary practices and diabetes risk factors is another critical barrier. Misconceptions, cultural beliefs, and limited access to reliable health information contribute to poor food choices and unhealthy lifestyles (Contento, 2016). Inadequate nutrition education and outreach programs further reduce the effectiveness of prevention efforts. Rapid urbanization and the rise of fast-food culture have significantly altered dietary behaviors. Urban populations often consume more convenience foods and engage in less physical activity due to time constraints and lifestyle changes (Popkin, 2017). Aggressive marketing of ultra-processed foods and sugary beverages has made unhealthy choices more accessible (Hawkes et al., 2015). Policy implementation gaps also limit success. Weak enforcement, inadequate funding, and poor coordination reduce the effectiveness of existing programs, while disparities between urban and rural areas lead to unequal health outcomes (WHO, 2022).

10. Future Directions and Innovations

The rising burden of diabetes necessitates innovative and forward-looking approaches that integrate advances in science, technology, and sustainability. Future strategies in public health nutrition must move beyond conventional models toward personalized, technology-driven, and environmentally sustainable solutions (World Health Organization, 2022). One promising approach is precision nutrition, which tailors dietary recommendations based on an individual's genetic makeup, metabolic profile, lifestyle, and gut microbiome. By recognizing individual variability in dietary responses, this approach can improve glycemic control and enhance adherence to dietary interventions (Ordovas et al., 2018). The use of artificial intelligence (AI) and digital health platforms is transforming diabetes care. AI-powered tools can analyze large datasets to predict disease risk, provide personalized dietary guidance, and monitor patient progress in real time. Mobile applications, wearable devices, and telemedicine platforms enable continuous tracking of glucose levels, diet, and physical activity, thereby improving access to care and promoting self-management (WHO, 2022; Beam & Kohane, 2018). Another key focus is the promotion of sustainable diets and climate-resilient foods. Crops such as millets, pulses, and indigenous grains are nutritionally rich, have a low glycemic index, and are environmentally sustainable. Encouraging their consumption can address both nutritional security and climate challenges (Food and Agriculture Organization, 2019). Integrating traditional knowledge with modern science offers a holistic pathway to improve nutrition outcomes. Traditional diets based on local, seasonal, and plant-based foods support metabolic health and cultural acceptability.

When combined with modern research and clinical evidence, such approaches can enhance the effectiveness of diabetes prevention and management strategies (WHO, 2022).

11. Conclusion

Diabetes has emerged as a major public health concern, driven by complex interactions between nutrition, lifestyle, socio-economic factors, and environmental influences. This chapter highlights that addressing diabetes requires more than clinical management; it demands a comprehensive public health nutrition approach that spans prevention, early detection, and long-term care. From understanding the disease burden and its determinants to exploring the critical role of diet, micronutrients, and behavior change, it is evident that nutrition lies at the core of both the etiology and management of diabetes. Public health nutrition strategies, including population-based interventions, community engagement, and supportive policy frameworks, play a crucial role in reducing risk and promoting healthier dietary patterns. At the same time, individual-level approaches such as nutrition literacy, lifestyle modification and self-care practices are essential for sustained glycemic control and improved quality of life. The integration of cultural, social, and economic considerations further strengthens the effectiveness and inclusivity of these interventions. Despite ongoing efforts, challenges such as food insecurity, lack of awareness, urbanization, and gaps in policy implementation continue to hinder progress. Addressing these barriers requires coordinated, multi-sectoral action involving governments, healthcare systems, communities, and individuals. Looking ahead, emerging innovations such as precision nutrition, digital health technologies, sustainable diets, and the integration of traditional knowledge with modern science offer promising pathways to enhance diabetes prevention and management.

A 360° approach combining science, society, and self-care is essential to effectively combat the growing diabetes epidemic. Strengthening public health nutrition systems and fostering collective responsibility can significantly reduce disease burden and pave the way toward healthier and more sustainable futures.

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