

Millets as Functional Cereals for the Management of Type 2 Diabetes Mellitus: Nutritional Composition, Mechanistic Pathways, and Clinical Evidence

Jessica Sarao¹, Akash Kumar¹, Ankush Kumar², Pankaj Prabhakar³, Meena Bishnoi⁴, Pragati Godara¹, Vaishali Soni¹, Shiv Kumar^{1*}

¹MMICT & BM (HM), Maharishi Markandeshwar (Deemed to be University), Mullana-133207, Haryana, India

²Advanced Centre of Research & Innovation, CGC University, Mohali, Punjab, India-140307

³School of Management Studies, CGC University, Mohali, Punjab, India-140307

⁴Maharani Govt. Girls Senior Secondary School, Bikaner, Rajasthan 334001, India

*Corresponding author: Dr. Shiv Kumar

Email id: shivk1999@gmail.com

Contact no. 8219968973

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ABSTRACT:

Millets are nutrient-dense functional cereals and have the potential for managing and preventing type 2 diabetes mellitus (T2DM). In comparison to refined cereals such as polished rice and wheat, millets are a good source of dietary fiber, resistant starch, minerals, vitamins, and bioactive phytochemicals. The bioactive profile, dietary fiber, and resistant starch of millets may contribute to improving metabolic health and attenuating the postprandial glycemic response. Studies have shown that millet-derived constituents modulate glucose metabolism through multiple pathways, including inhibition of carbohydrate-hydrolyzing enzymes, improvement of insulin signaling, modulation of the gut microbiota, and suppression of oxidative stress and systemic inflammation. The superior nutritional profile, low environmental footprint, and inherent climate resilience of millets further position them as a sustainable therapeutic approach amid the rising global burden of diabetes. This narrative review comprehensively examines the nutritional profile of millet varieties, the mechanistic pathways highlighting their anti-diabetic effects, clinical trial evidence, and future research directions relevant to millet integration into diabetes management strategies.

Keywords: Bioactive phytochemicals; Insulin resistance; Gut microbiota; Anti-diabetic mechanisms; Clinical trials.

1. Introduction

The global food system depends on a very small number of crop species. Among carbohydrate-providing crops, three related species (wheat, rice,

and maize) account for the vast majority of human caloric intake worldwide. This dependence may lead to systemic vulnerabilities of food security, particularly in an era of climate change, soil

degradation, and population growth. Therefore, there is a need to add underutilized, climate-resilient crops to the global food basket (Dogra & Awasthi, 2015). Cereal grains are essential to the human diet across every culture, as well as for animal feed. The cereal species of agricultural significance include wheat, rye, barley, oats, maize, rice, sorghum, and millets (Wrigley C. W., 2010).

Against this background, the global epidemic of type 2 diabetes mellitus (T2DM) presents a significant public health challenge. T2DM is the most common chronic metabolic condition prevalent around the world, with complications such as cardiovascular disorders, kidney damage, neuropathy, and retinopathy (Almaski et al., 2019). In India, a study published in 2023 by the Indian Council of Medical Research (ICMR) estimated the number of people living with diabetes at approximately 101 million, resulting in India one of the diabetes capitals of the world (Ministry of Health and Family Welfare, 2023). Globally, projections indicate a 51% surge in the diabetic population by 2045 if current trends persist, driven primarily by urbanization, sedentary lifestyles, and the widespread adoption of energy-dense, fiber-poor diets (Anitha et al., 2021). The irreversible organ damage associated with poorly managed T2DM, including renal failure, loss of vision, cardiac dysfunction, and hepatic compromise, highlights the need for safe, accessible, and sustainable preventive and therapeutic strategies (Demir et al., 2021).

Dietary modification occupies a central position among these strategies. The studies suggest that the millets may play a crucial role in attenuating postprandial glycemic spikes, reducing fasting blood glucose concentrations, lowering the insulin index and insulin resistance, decreasing cardiovascular risk associated with chronic hyperglycemia, and improving glycosylated hemoglobin (HbA1c) levels over sustained consumption (Kam et al., 2016; Baniwal et al., 2021). These benefits are attributable to millets' distinctive compositional profile. For example, wheat, barley, and rye contain gluten, a complex mixture of prolamins and glutenins characterized by high concentrations of proline and glutamine residues that render them largely

resistant to gastrointestinal proteolysis. This structural resistance causes immunopathological conditions such as celiac disease and non-celiac gluten sensitivity, limiting the suitability of these cereals for metabolically vulnerable subpopulations (Comino et al. 2013). Millets are gluten-free and rich in slow-digesting carbohydrates, dietary fiber, and a wide range of bioactive compounds, offering a nutritionally superior and clinically relevant alternative (Gupta, V. (2023)).

In recent years, millet grains have attracted significant scientific interest. Beyond their adequate starch-derived energy content, millets are recognized for their high-quality protein, dietary fiber, lipid profiles enriched with unsaturated fatty acids, and abundant micronutrient content including calcium, iron, potassium, B-vitamins, phosphorus, magnesium, zinc, copper, and manganese (Sangeeta and RB Grewal, 2018; Alencar, & Oliveira, 2019; Rathore et al., 2016; Anitha et al., 2021). Their relatively low glycemic index, a consequence of their fiber and resistant starch content, is of direct therapeutic relevance to T2DM management. India alone cultivates at least nine widely grown millet varieties, including pearl, finger (ragi), foxtail, sorghum, proso, barnyard, Kodo, little millet, and red millet, each with a distinct nutritional fingerprint. Furthermore, millets contribute negligibly to the carbon footprint, demand little water, and thrive in high-temperature, low-rainfall environments where conventional cereals fail. (Anitha et al., 2021; Muthamilarasan et al., 2016).

Despite this promise, millets remain underutilized in mainstream dietary guidelines and in the clinical nutrition literature relative to their potential. While individual studies have examined the properties of specific millet species or isolated bioactive compounds, a combined, evidence-based narrative that integrates their nutritional composition, anti-diabetic mechanisms, and clinical outcomes remains limited. The present narrative review addresses this gap by systematically and critically synthesizing the current state of knowledge across these domains, with the goal of informing researchers, clinicians, nutritionists, and policymakers about the therapeutic potential of

millets as functional cereals in the global fight against T2DM.

2. Nutritional Composition of Millets

Millets, being a heterogeneous group of small-seed coarse grains belonging to the *Poaceae* family, have re-emerged in modern nutritional science as functional cereals having exceptional density and dietary value (Ceasar et al., 2022; Maitra et al., n.d.). The United Nations General Assembly declared the year 2023 as the International Year of Millets (Ayofemi et al., 2023). Millets constitute a heterogeneous group of small-seeded coarse grains belonging to the family *Poaceae*. Often designated as "Nutri-cereals," they surpass conventional refined cereals across several key nutritional parameters while simultaneously offering a moderate glycemic index (Sabuz et al., n.d.; Saleem et al., 2023). The following sections examine the proximate composition, amino acid profile, and bioactive phytochemical content of the major millet varieties.

2.1. Proximate Composition

The proximate composition of millets varies across species but consistently reflects a nutritional profile superior to that of refined wheat flour or polished rice. Millets comprise about 60-75% carbohydrate on a dry-weight basis and are constituted primarily by complex polysaccharides rather than readily digestible simple sugars (Kalsi & Bhasin, 2023). Carbohydrate content in finger millet, foxtail millet, proso millet, Kodo millet, and sorghum is 72.6, 60.9, 70.4, 66.6, and 67.7 g/100 g, respectively, while pearl millet provides approximately 67 g/100 g (Mohapatra et al., 2019; Tripathi et al., 2021). The main characteristic of millet carbohydrates is their slow digestion, which is attributable to the resistant starch fraction, an intact cell wall matrix, and tannin-starch interactions that collectively impede enzymatic hydrolysis and attenuate postprandial glycemic responses (Saleem et al., 2023; Sharma & Gujral, 2019).

Millets are also notably rich in dietary fiber. Crude fiber content ranges from approximately 1.2 to 9.0 g/100 g, with Kodo millet and barnyard millet representing the most fiber-dense varieties

(Mohapatra et al., 2019; Tripathi et al., 2021). The fiber fraction comprises both soluble and insoluble components, including arabinoxylans, β -glucans, and cellulose, which contribute to delayed gastric emptying, increased fecal bulk, and provision of fermentable substrate for the colonic microbiota. These polysaccharides are fermented by colonic bacteria to produce short-chain fatty acids that exert systemic effects on lipid metabolism, gut barrier integrity, and glucose homeostasis (Dekka et al., 2023; Goff et al., n.d.). The mechanistic links between millet dietary fiber and reduced α -amylase activity, slower gastric emptying, and beneficial modulation of intestinal microbiota composition have been documented in several studies (Anitha et al., n.d.; Samtiya et al., n.d.).

Millet proteins range from 7.7-12.5% of dry grain weight (Mohapatra et al., 2019; Tripathi et al., 2021). Proso millet leads with approximately 12.5 g/100 g, followed closely by foxtail millet (12.3 g) and pearl millet (11.6 g), while finger millet contains the lowest protein content among commonly studied varieties at approximately 7.7 g/100 g (Arya et al., 2022; Tripathi et al., 2021). Fat content in millets is moderate, ranging from approximately 1.0 to 5.0 g/100 g. Pearl millet is the most lipid-rich variety at approximately 5.0 g/100 g, while finger millet and Kodo millet remain at the lower end of the spectrum at approximately 1.5 g and 1.4 g per 100 g, respectively (Amir et al., 2023; Tripathi et al., 2021). Pearl millet contains approximately 5.0 grams of fat per 100 grams, making it the most lipid-rich common variety, while finger millet and Kodo millet remain at the lower end of the spectrum at approximately 1.5 and 1.4 grams, respectively (Tripathi et al., 2021). The lipid profile of millets is dominated by unsaturated fatty acids, which contribute to the favorable atherogenic and lipidemic effects observed in clinical and animal studies (Lee et al., 2010). The combination of relatively low total fat content and a favorable polyunsaturated-to-saturated fatty acid ratio positions millets as cardioprotective cereals suitable for populations at risk of dyslipidaemia and metabolic syndrome. Balkrishna, A. (2024)

Table 1. Proximate Composition of Major Millet Varieties (per 100 g edible portion, dry weight basis)

Nutrient	Pearl Millet (<i>Pennisetum glaucum</i>)	Finger Millet (<i>Eleusine coracana</i>)	Foxtail Millet (<i>Setaria italica</i>)	Proso millet (<i>Panicum miliaceum</i>)	Kodo Millet (<i>Paspalum scrobiculatum</i>)	Barnyard Millet (<i>Echinochloa frumentacea</i>)	Little Millet (<i>Panicum sumatrense</i>)	Sorghum (<i>Sorghum bicolor</i>)	Refined Wheat	Polished Rice
Energy (kcal)	361	328	351	354	353	342	346	349	346	345
Protein (g)	11.6	7.7	12.3	12.5	8.3	11.2	7.7	10.4	11.8	6.8
Carbohydrates (g)	67.0	72.6	60.9	70.4	66.6	65.5	67.0	67.7	71.2	78.2
Total Fat (g)	5.0	1.5	4.3	1.1	1.4	3.9	4.7	1.9	1.5	0.5
Crude Fiber (g)	1.2	3.6	8.0	2.2	9.0	10.1	7.6	1.6	1.2	0.2
Total Dietary Fiber (g)	8.5	11.5	14.0	8.5	11.8	13.6	9.8	10.2	2.7	2.8
Mineral Matter / Ash (g)	2.3	2.7	3.3	1.9	2.6	4.4	1.5	1.6	1.7	0.6
Moisture (g)	12.4	13.1	11.2	12.5	12.8	11.9	11.5	11.9	12.8	13.7

Sources: Tripathi et al. (2021); Mohapatra et al. (2019); Ali et al. (2003); Li et al. (2008); Arya & Bisht (2022); Sabuz et al. (2023).

2.2.Amino Acid Composition

The protein quality of millets is determined not only by total quantity but by the composition and balance of essential and limiting amino acids. Among the millet varieties, sorghum exhibits the most balanced essential amino acid distribution, with relatively high concentrations of lysine, tryptophan, phenylalanine, tyrosine, isoleucine, valine, leucine, and threonine (Ratnavathi et al., 2022). Lysine content varies considerably across varieties; finger millet provides approximately 2.2 g per 100 g of protein, while pearl millet provides approximately 2.7 g (Mohapatra et al., 2019; Tripathi et al., 2021). Although millet proteins generally contain less lysine than animal-derived

proteins, food processing techniques such as germination, fermentation, and malting significantly improve the digestibility and bioaccessibility of essential amino acids. Germination has been shown to increase water-soluble protein fractions and promote the synthesis of antioxidant peptides, while controlled fermentation of pearl millet improves in vitro protein digestibility (Ali et al., n.d.; J. Li et al., 2008). The inclusion of branched-chain amino acids at significant concentrations further supports the role of millet protein in muscle protein synthesis and energy metabolism, particularly for communities dependent on plant-based protein sources.

Table 4. Essential and Non-Essential Amino Acid Profile (mg per g protein)

Amino Acid	Pearl Millet	Finger Millet	Foxtail Millet	Proso Millet	Kodo Millet	Sorghum
Essential Amino Acids						
Lysine	27	22	14	19	13	21
Tryptophan	16	11	11	8	14	12
Histidine	21	20	17	17	11	22
Phenylalanine	51	51	51	51	50	49

Tyrosine	30	36	26	–	–	30
Methionine	21	21	18	15	14	14
Cysteine	17	14	22	–	11	12
Threonine	35	39	25	26	27	31
Isoleucine	39	41	39	41	–	38
Valine	51	60	57	53	41	51
Leucine	91	99	152	110	87	137
Non-Essential Amino Acids						
Arginine	36	32	25	28	–	32
Aspartic acid	70	65	64	60	58	63
Glutamic acid	220	230	215	195	200	218
Glycine	25	38	23	22	24	28
Alanine	86	65	100	95	80	95
Serine	45	56	50	48	47	42
Proline	65	73	75	60	63	78

The limiting amino acid in most millets (except sorghum) is **lysine**. Sorghum demonstrates the most balanced essential amino acid distribution. Sources: Tripathi et al. (2021); Mohapatra et al. (2019); Ali et al. (2003); Ratnavathi & Tonapi (2022).

3. Micronutrient Composition

3.1 Minerals

The mineral content of millets substantially exceeds that of most refined staple grains, further enhancing their nutritional value. Finger millet is exceptional in this regard, being the highest calcium-containing cereal, providing 344-364 mg of calcium per 100 g, which is approximately ten times the calcium content of rice or wheat. This makes finger millet a strategically important dietary option for populations at risk of osteoporosis, growing children, lactating women, and individuals following plant-predominant diets without dairy inclusion (Srivastava et al., 2021; Tripathi et al., 2021).

Iron content also varies considerably across millet varieties. Pearl millet, foxtail millet, proso millet, and Kodo millet provide approximately 8.0, 2.8, 2.9, and 0.5 mg of iron per 100 g, respectively (Mohapatra et al., 2019; Tripathi et al., 2021). Pearl millet has been the most extensively targeted variety in biofortification initiatives, and iron- and zinc-biofortified pearl millet varieties have

demonstrated significant improvements in hemoglobin levels and cognitive performance in Indian children and adolescents in randomized controlled trials (Mehta et al., n.d.; Scott et al., n.d.). The presence of phytates and polyphenols in millets can reduce iron absorption; however, this inhibitory effect can be substantially mitigated through processing techniques such as soaking, germination, fermentation, and malting (Kadapa et al., 2023).

Millets are also rich in phosphorus, which supports bone mineralization and energy transfer via ATP (Tripathi et al., 2021). Zinc concentrations range from 1.6 to 3.7 mg/100 g across varieties, and zinc is essential for immune function, growth, and wound healing (Satyavathi et al., 2021). Magnesium is abundantly present in millets and, while not always included in comparative nutrient tables, plays a critical role in glucose metabolism, neuromuscular regulation, and blood pressure control. Dietary supplementation with foxtail millet has been associated with significant reductions in diastolic blood pressure in hypertensive individuals (Hou et al., 2018).

Table 2. Mineral Content of Major Millet Varieties (mg per 100 g)

Mineral	Pearl Millet	Finger Millet	Foxtail Millet	Proso Millet	Kodo Millet	Barnyard Millet	Little Millet	Sorghum
Calcium (Ca)	42	344–364	31	14	27	20	17	25
Iron (Fe)	8.0	3.9	2.8	2.9	0.5	5.0	9.3	4.1
Phosphorus (P)	296	283	290	206	188	280	220	222
Magnesium (Mg)	137	137	81	153	147	82	133	171
Zinc (Zn)	3.1	2.3	2.4	1.4	0.7	3.0	3.7	1.6
Potassium (K)	307	408	250	113	144	220	129	363
Sodium (Na)	10.9	11	4.6	8.2	4.6	8.1	8.1	7.3
Copper (Cu)	1.06	0.47	1.40	0.80	1.60	0.60	1.00	0.46
Manganese (Mn)	1.15	5.49	0.60	0.60	1.10	0.96	0.68	1.10
Selenium (Se), µg	2.7	4.5	7.7	2.5	0.9	6.4	2.0	12.4

Sources: Tripathi et al. (2021); Mohapatra et al. (2019); Ratnavathi & Tonapi (2022); Satyavathi et al. (2021); Arya & Bisht (2022).

3.2 Vitamins

Millets are rich primarily in B vitamins, notably thiamine (B1), riboflavin (B2), and niacin (B3), all of which are indispensable for the metabolism of carbohydrates, lipids, and amino acids. Thiamine content ranges, on average, from 0.30 to 0.59 mg/100 g (Tripathi et al., 2021). Niacin content in pearl millet is approximately 2.8 mg/100 g, with similar concentrations reported in sorghum; niacin is essential for NAD- and NADP-dependent metabolic reactions (Mohapatra et al., 2019;

Tripathi et al., 2021). Riboflavin levels in millets are also nutritionally significant, particularly in populations for which millets constitute a dietary staple. Millets are not significant sources of fat-soluble vitamins (A, D, E, and K) in their raw form; however, sprouted and germinated millet preparations have been shown to develop measurable amounts of vitamin C and elevated tocopherol (vitamin E) concentrations, thereby enhancing their overall micronutrient value (Paschapur et al., 2021).

Table 3. Vitamin Content of Major Millet Varieties (mg per 100 g unless stated)

Vitamin	Pearl Millet	Finger Millet	Foxtail Millet	Proso Millet	Kodo Millet	Barnyard Millet	Sorghum
Thiamine (B1)	0.33	0.42	0.59	0.41	0.15	0.33	0.35
Riboflavin (B2)	0.25	0.19	0.11	0.28	0.09	0.10	0.14
Niacin (B3)	2.80	1.10	3.20	4.50	2.00	4.20	4.30
Pantothenic acid (B5)	1.09	1.30	0.82	0.85	0.63	0.58	0.21
Pyridoxine (B6)	0.27	0.30	0.30	0.41	0.07	0.39	0.40
Folate (B9), µg	36	34	15	9	39	36	20
Vitamin E, mg	0.05	0.22	0.31	0.15	–	0.50	0.50
β-carotene, µg	132	42	90	73	–	–	47

Vitamin K, µg	0.9	–	–	–	–	–	–
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Sources: Tripathi et al. (2021); Sabuz et al. (2023); Samtiya et al. (2023); Saleem et al. (2023).

4. Bioactive Compounds and Phytochemicals

Beyond conventional macronutrients and micronutrients, millets contain abundant bioactive secondary metabolites that underpin their functional food status. Phenolic acids, including ferulic, p-coumaric, caffeic, vanillic, and chlorogenic acids, are widely distributed across millet varieties, with finger millet and barnyard millet demonstrating particularly high concentrations (Kuruburu et al., 2022; H. Wang et al., 2022). Flavonoids, including apigenin, luteolin, kaempferol, catechin, and quercetin, contribute to antioxidant defense, anti-inflammatory signaling, and modulation of insulin sensitivity(Samtiya et al., 2021). Tannins are specifically abundant in finger

millet and sorghum;tannins exert a dual role by reducing protein and mineral bioavailability while simultaneously contributing antioxidant and antidiabetic activity (Nithiyanantham et al., 2019).

Other important phytochemicals include phytosterols, lignans, saponins, and phytic acid. The phytic acidhas mineral chelation activity that reduces bioavailability while exhibiting antioxidant and chemopreventive properties (Islam et al., 2021). The bioactive compound profile of millets has been mechanistically associatedwith reduced LDL-cholesterol synthesis, enhanced cholesterol excretion, inhibition of cholesterol absorption, and downregulation of inflammatory cytokines (Nishizawa et al., 2009; Singh et al., 2020).

Table 5. Bioactive Compounds, Antioxidant Capacity, and Functional Properties

Parameter	Pearl Millet	Finger Millet	Foxtail Millet	Proso Millet	Kodo Millet	Barnyard Millet	Sorghum
Total Phenolic Content (mg GAE/100 g)	365–488	378–605	106–177	65–270	220–407	142–520	170–10,260
Total Flavonoid Content (mg CE/100 g)	35–185	92–375	28–106	16–60	110–270	28–230	16–410
Tannins (mg/100 g)	110–275	280–715	18–35	10–25	35–85	50–110	58–9,600
Phytic acid (mg/100 g)	354–796	250–820	175–280	230–710	180–460	125–500	460–960
Saponins (mg/100 g)	84	220	110	95	105	95	165
DPPH Radical Scavenging (%) inhibition)	28–62	45–88	22–55	18–48	30–72	35–80	40–95
Estimated Glycemic Index	55–62	54–68	50–58	60–67	49–54	41–50	58–70
Resistant Starch (g/100 g)	5.6	4.2	3.8	4.0	6.8	8.2	5.4

Sources: Wang et al. (2022); Ofozu et al. (2020); Anis & Sreerama (2020); Krishnan et al. (2022); Samtiya et al. (2021); Kuruburu et al. (2022); Saleem et al. (2023).

3. Mechanistic Pathways Underlying Anti-Diabetic Activity

The anti-diabetic effects of millets are not attributable to any single constituent or mechanism

but emerge from the concerted action of multiple nutritional and phytochemical components operating across several physiological systems. The major mechanistic pathways identified in

preclinical and mechanistic research are discussed below and presented in Figure 1.

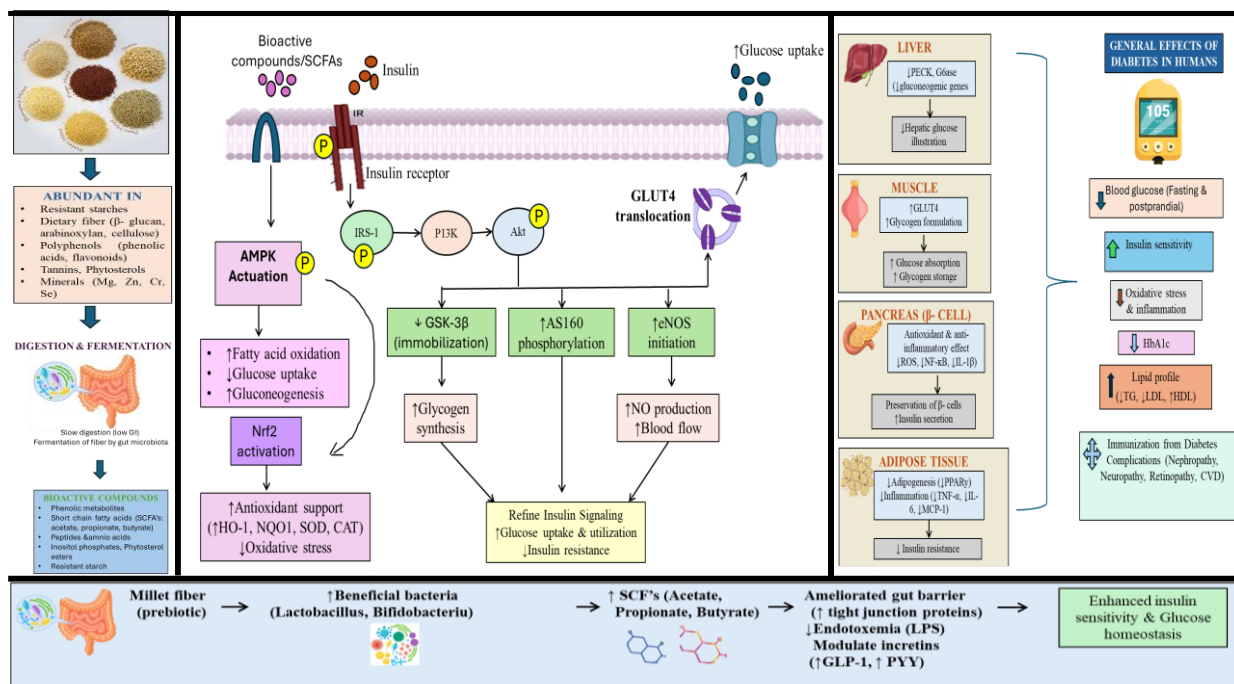


Figure 1. Mechanisms involved in the regulation of glycemic control and diabetes management through millet consumption.

3.1. Modulation of Carbohydrate-Hydrolysing Enzymes

Millet reduces the spikes in postprandial blood sugar levels mainly due to their ability to inhibit the brush border and pancreatic digestive enzymes that are responsible for carbohydrate hydrolysis, namely, α -amylase and α -glucosidase (Krishnan et al., 2022). Since phenolic compounds present in millets inhibit the conversion of starch to glucose, they also help mitigate postprandial hyperglycemia. In vitro studies done by Ofofu et al. show that the ethanolic extract of Italian finger millet and barnyard millet exhibited α -glucosidase inhibition at an IC_{50} of approximately 18.07 μ g/mL and 20.90 μ g/mL, respectively, which is much lower and better than the IC_{50} of 59.34 μ g/mL for the drug acarbose, which is considered to be a benchmark for such activity. Similarly, α -amylase inhibition by Italian finger millet (IC_{50} = 10.56 μ g/mL) was superior to acarbose's inhibition (IC_{50} = 27.73 μ g/mL), highlighting that certain millet varieties possess enzymatic inhibitory properties comparable to or even exceeding those of conventional drugs (Ofofu et al., 2020). Complementary evidence from millet bran dietary

fiber further indicates a structural and viscosity-mediated barrier to enzyme–substrate contact, which compounds the kinetic inhibition described above (CAO et al., 2018). Collectively, these findings establish that the carbohydrate-restricting action of millets functions through both phenolic-mediated competitive inhibition and physical entrapment of starch within fibre-rich gel matrices.

3.2. Activation of the PI3K/AKT Insulin Signalling Pathway

Insulin resistance in T2DM is characterized by attenuated signalling through the phosphatidylinositol 3-kinase (PI3K)/protein kinase B (AKT) cascade, which normally orchestrates glucose uptake, glycogen synthesis, and suppression of hepatic glucose production (W. Wang et al., 2022). Millet bioactive seems to restore this signaling axis through multiple converging actions. In streptozotocin-induced diabetic mice, protein isolates from raw and cooked foxtail millet increased the phosphorylated forms of AKT and PI3K, while simultaneously enhancing the expression of the glucagon-like peptide-1 receptor (GLP-1R) and

downregulating stearoyl-CoA desaturase 1 (SCD1)(Y. Fu et al., 2021). The ensuing cascade facilitates insulin-dependent glucose disposal by promoting the translocation of glucose transporter type 4 (GLUT4) to the plasma membrane in skeletal muscle and adipose tissue. Additionally, phenolic-rich extracts from foxtail millet bran have been shown to increase hepatic GLUT2 expression in diabetic models, enhancing hepatocyte glucose uptake and supporting systemic euglycemia(Shi et al., 2024). Activation of PI3K/AKT downstream of insulin receptor substrate (IRS) phosphorylation also inactivates glycogen synthase kinase-3 (GSK-3), enabling glycogen synthesis and effectively sequestering circulating glucose(Yang et al., 2023).

3.3. Suppression of Gluconeogenesis and Stimulation of Glycolysis

Hepatic overproduction of glucose via gluconeogenesis is a descriptive feature of T2DM and a vital driver of fasting hyperglycaemia (Chung et al., 2015). Millet consumption seems to adjust this hepatic flux. Foxtail millet has been shown to downregulate phosphoenolpyruvate carboxykinase (PEPCK), a key gluconeogenic enzyme, whose reduction decreases new glucose synthesis and limits glucose output from the liver(Ren et al., 2021; Yu et al., 2021). Concurrent downregulation of fructose-1,6-bisphosphatase enhances glucose-stimulated insulin secretion and improves the cellular ATP-to-ADP ratio, a critical trigger for β -cell exocytosis of insulin(Zhang et al., 2010). Beyond suppressing gluconeogenic enzymes, millet phenolics upregulate phosphofructokinase-1, promoting glycolytic flux and ensuring absorbed glucose is preferentially directed toward energy production instead of circulating as a hyperglycemic load(Hatting et al., 2018). In murine diabetic models, prolamin from cooked foxtail millet has been associated with inhibition of gluconeogenesis, activation of glycolysis, and modulation of starch, sucrose, and galactose metabolism(Y. Fu et al., 2020). Through this dual mechanism of restrictive endogenous glucose liberation and its rapid peripheral utilization, millets prove to provide a metabolically favourable substrate environment.

3.4. Preservation of Pancreatic β -Cell Function and Insulin Excretion

Progressive β -cell exhaustion is a key feature in the natural progression of type 2 diabetes mellitus (T2DM), where chronic glucotoxicity, lipotoxicity, and cytokine-mediated apoptosis together diminish insulin secretory capacity(Z. Fu et al., 2012). Evidence suggests that millet bioactive compounds protect β -cell mass and function. Korean proso millet protein concentrate has been shown to increase plasma adiponectin and high-density lipoprotein cholesterol (HDL-C) while reducing tumor necrosis factor- α (TNF- α), creating a favorable environment for improved insulin sensitivity and β -cell preservation(Park et al., 2008). Adiponectin on its own elaborates insulin signalling and modulates phosphoenolpyruvate carboxykinase and glucose-6-phosphatase activity (Adiyaman et al., 2019). In addition, millet protein hydrolysates exhibit effective dipeptidyl peptidase-IV (DPP-IV) inhibitory activity, having an inhibition potential of approximately 75.7% after three hours of enzymatic hydrolysis. This activity aids in extending the action of endogenous incretin hormones, incorporating GLP-1 (Gu et al., 2021). Research indicates that the polyphenol fraction of foxtail millet has been observed to stimulate GLP-1 secretion from intestinal L-cells, thereby amplifying glucose-dependent insulin secretion through cAMP-mediated activation of protein kinase A within β -cells (Gromada et al., 2004; Yuxuan et al., 2023a). The antioxidant phenolics and flavonoids of millet also shield β -cells from reactive oxygen species (ROS)-mediated apoptosis, a critical safeguard given the islet's intrinsically modest antioxidant defences(W. Li et al., n.d.).

3.5. Attenuation of Chronic Inflammation

Low-grade systemic inflammation is now recognized as both a cause and a consequence of insulin resistance, with cytokines such as TNF- α , interleukin-6 (IL-6), and interleukin-1 β (IL-1 β) interfering with insulin receptor signalling and promoting β -cell dysfunction (Al-Mansoori et al., 2022; Tsalamandris et al., 2019). The nuclear factor-kappa B (NF- κ B) pathway sits at the centre of this inflammatory axis, and several millet-

derived compounds appear to dampen its activation. Foxtail millet bran polyphenols reduce the transcription of pro-inflammatory mediators while allowing the development of anti-inflammatory cytokines via blocking the nuclear translocation of the NF- κ B p65 subunit. (Shi et al., 2015). Supplementing diabetic rat models with foxtail millet has been linked to attenuation of I κ B kinase phosphorylation and decreases in C-reactive protein, IL-6, and TNF- α (Ren et al., 2021). In mouse models fed high-fat, high-fructose diets, germinated millet flour has been proven effective in lowering inflammation, oxidative stress, and hepatic steatosis (Theodoro et al., 2021). Millets successfully restore the integrity of insulin signalling at the molecular level by blocking the cytokine-driven serine phosphorylation of insulin receptor substrate proteins.

3.6. Mitigation of Oxidative and Nitrosative Stress

Hyperglycaemia-induced overproduction of mitochondrial ROS disrupts insulin signalling, impairs GLUT4 translocation, and accelerates microvascular complications (Banday et al., 2020). Millets, particularly finger millet and barnyard millet, are rich in phenolic acids—including p-coumaric, ferulic, and chlorogenic acids—as well as flavonoids such as apigenin, kaempferol, and catechin, all of which exhibit potent free radical scavenging activity (Anis et al., n.d.; Jayawardana et al., 2021). In a twelve-week intervention in mice fed a high-fat diet, finger millet bran and whole-grain supplementation reduced nitrite concentrations in visceral adipose tissue and pancreas while elevating glutathione levels in adipose depots and the liver, indicative of enhanced redox homeostasis (Murtaza et al., 2014). Feruloylated xylo-oligosaccharides extracted from pearl millet bran also exhibit substantial antiglycation activity, with inhibition rates approaching 87.7% in late-stage glycation assays, thereby curtailing the formation of advanced glycation end-products that drive diabetic complications (Singh et al., 2021). By neutralizing ROS and reactive nitrogen species, millet phenolics preserve the catalytic integrity of insulin signalling components and protect pancreatic islets from oxidative apoptosis.

3.7. Hormonal Regulation: Leptin, Ghrelin, and Incretins

Glycaemic homeostasis is intimately linked to the hormonal control of appetite and energy expenditure. Millet consumption has been shown to elevate circulating leptin concentrations, which act centrally to suppress appetite via interactions with neuropeptide Y and pro-opiomelanocortin neurons in the hypothalamus, while also stimulating cholecystokinin release to reinforce satiety (Al-Hussaniy et al., 2021; Ren et al., 2021). The increase in GLP-1 secretion observed following polyphenol-rich foxtail millet consumption produces a coordinated decrease in ghrelin, the orexigenic hunger hormone, partly mediated by the insulinotropic action of GLP-1 (Hagemann et al., 2007; Yuxuan et al., 2023). Activation of the GLP-1 receptor on pancreatic β -cells stimulates adenylate cyclase, raises intracellular cAMP, and engages both protein kinase A and the cAMP-regulated guanine nucleotide exchange factor II, culminating in glucose-dependent insulin secretion without the hypoglycaemic risk associated with sulfonylureas (Gromada et al., 2004). This integrated hormonal modulation aligns appetite regulation with improved glycaemic control, offering a holistic mechanism that distinguishes millets from single-target pharmacological agents.

3.8. Modulation of the Gut Microbiota and Short-Chain Fatty Acid Production

A growing body of evidence implicates gut dysbiosis in the pathogenesis of T2DM, with diabetic individuals exhibiting reduced microbial diversity, decreased butyrate-producing taxa, and increased intestinal permeability that permits lipopolysaccharide translocation and metabolic endotoxemia (Allin et al., 2015; Cani et al., 2007). Millets, owing to their content of resistant starch, non-starch polysaccharides, and bound phenolics, function as potent prebiotic substrates. Heat-treated foxtail millet protein increases the relative abundance of beneficial taxa such as *Bifidobacterium*, *Lactobacillus*, and members of the family *Erysipelotrichaceae*, while suppressing pathobionts including *Marvinbryantia* and *Dubosiella* (H. Wang, Fu et al., n.d.; H. Wang, Shen, et al., n.d.). Prolamin

from cooked foxtail millet enriches *Akkermansia*, *Odoribacter*, and *Blautia*, taxa associated with improved gut barrier integrity and reduced systemic inflammation (Y. Fu et al., 2020). Finger millet bran similarly augments *Roseburia* populations in murine models of diet-induced obesity (Murtaza et al., 2014). The downstream consequence of this microbial shift is enhanced production of short-chain fatty acids—particularly butyrate—which serves as the preferred energy substrate for colonocytes, fortifies tight-junction integrity, suppresses pro-inflammatory cytokines such as IL-6 and IL-12, and promotes hepatic glycogen synthesis while restraining gluconeogenesis [41,42]. Through this microbiota-metabolite axis, millets exert a systemic anti-diabetic influence that extends well beyond direct enzymatic inhibition.

3.9. Inhibition of Glucose Transporters SGLT1 and SGLT2

Sodium-glucose co-transporters in the intestinal brush border (SGLT1) and renal proximal tubule (SGLT2) are pharmacological targets of contemporary anti-diabetic agents such as the gliflozins. Millet bioactive appears to recapitulate, at least in part, this mechanism by attenuating SGLT-mediated glucose absorption and reabsorption (Kumar et al., 2024). By reducing intestinal glucose uptake at the apical membrane and limiting renal glucose reclamation, millet phenolics complement their inhibition of luminal carbohydrate digestion, producing a more gradual and lower-amplitude postprandial glycaemic curve. Although direct molecular evidence in human cohorts remains limited, *in vitro* and *in vivo* studies support the notion that millet polyphenols engage these transporters as part of a multi-pronged glucose-lowering strategy.

4. Clinical Evidence

Clinical investigations into the metabolic effects of millets have employed a range of study designs, from acute single-meal crossover trials to multi-week dietary interventions. The study involves millet varieties based on various products such as porridge, flatbread, fermented pancakes (dosa), dumplings (mudde), muffins, and multi-ingredient

functional food mixes. Table 1 summarizes the clinical studies evaluating the impact of millet consumption on glycaemic, insulinaemic, gastrointestinal, hormonal, and broader cardiometabolic health. Alyami et al. provide some of the most mechanistically detailed data on the acute postprandial physiology of millet porridges in healthy individuals. In a pilot study (Alyami et al., 2017), seven healthy participants who completed all four meal conditions consumed isoenergetic porridges made from finger millet, pearl millet, Scottish oats, and rye. Postprandial gastric volumes were tracked using MRI at baseline and hourly for up to three hours, while blood glucose was sampled at 15 to 20-minute intervals over 120 minutes. Gastric volume area under the curve (AUC) was significantly higher for pearl millet than oats and rye ($p < 0.001$ in the $n = 10$ paired subgroup). Although the incremental AUC (iAUC) for blood glucose did not differ significantly across porridges, pearl millet was associated with lower postprandial hunger scores ($p = 0.01$), and a significant negative correlation was found between total gastric volume AUC and average appetite AUC ($r = -0.47$, $p < 0.010$). These findings suggest that slower gastric emptying induced by pearl millet may be a mechanistic pathway underlying its appetite-suppressing effects. In a subsequent larger randomised two-way crossover trial (Alyami et al., 2019), pearl millet porridge was directly compared with Scottish oats porridge with the addition of hormonal measurements. Consistent with the pilot data, iAUC for blood glucose over two hours did not differ significantly between meals ($P > 0.05$), confirming glycaemic equivalence with a well-established healthy grain. However, iAUC for gastric volume was significantly greater for pearl millet ($P = 0.045$), reinforcing the hypothesis of slower gastric transit. iAUC for glucose-dependent insulinotropic polypeptide (GIP), an incretin hormone implicated in adipose tissue triacylglycerol (TAG) absorption, was significantly lower for pearl millet compared to oats ($P = 0.001$). Other hormonal responses, including GLP-1, PYY, and insulin, as well as appetite ratings, were comparable between meals. These two studies demonstrated that pearl millet induces glycaemic

and physiological responses comparable to those of well-studied Western grains, while potentially offering additional metabolic benefits related to gastric dynamics and incretin secretion.

Almaski et al. (2022) conducted a single-blind randomised controlled crossover trial at Oxford Brookes Centre for Nutrition and Health, enrolling 15 healthy individuals and 14 individuals with prediabetes. Participants consumed a finger millet muffin or a matched wheat muffin on separate occasions, with measurements of glycaemic response (GR), insulin response (IR), gastric emptying (GE), and satiety over 3 to 4 hours post-consumption. A significant group-by-muffin

interaction was observed for IR iAUC at 180 minutes ($P = 0.042$), driven by a selective reduction in insulin response specifically in the prediabetic group fed the millet muffin. The peak glycaemic response was also significantly lower for the millet muffin compared to wheat ($P = 0.013$), and a significant effect on gastric emptying ascension time was noted ($P = 0.017$), consistent with slower gastric transit for the millet product. No significant effect on satiety AUC was detected. This study is particularly for demonstrating a differential metabolic benefit of finger millet in individuals with impaired insulin metabolism, suggesting that grain choice may be especially relevant for those at high risk of progressing to T2DM.

Table 1. Summary of Clinical Studies Evaluating Millet-Based Foods on Glycaemic

Study Design	Population (n, Condition)	Millet Type / Intervention	Duration / Measurements	Key Glycaemic& Insulinaemic Outcomes	Other Key Outcomes	Refereces
Pilot crossover MRI study	Healthy adults; n=7 (complete protocol); n=10 (subgroup); n=15 for oats/rye arms	Isoenergetic porridges: - Finger millet (FMP) - Pearl millet (PMP) - Scottish oats (SOP) - Rye (RP)	Single meal; MRI at baseline then hourly x3h; Blood glucose at baseline then every 15-20 min to 120 min; VAS appetite	iAUC blood glucose: not significantly different between meals; trend to lower iAUC for PMP; Gastric volume AUC significantly higher for PMP vs oats/rye (n=10; $p<0.001$)	Hunger lower for PMP vs oats/rye (n=10; $p=0.01$); Significant negative correlation: gastric volume AUC vs appetite AUC ($r=-0.47$; $p<0.010$)	Alyami et al. (2017)
Randomised two-way crossover trial	Healthy adults; n=26	Pearl millet porridge (PMP) vs Scottish oats porridge (SOP); isoenergetic and isovolumetric; served with water	Single meal; Blood glucose, hormones + MRI at baseline & 2h; Ad libitum lunch; Food intake diary for remainder of day	iAUC2h blood glucose: not significantly different ($P>0.05$); iAUC2h gastric volume: larger for PMP ($P=0.045$); iAUC2h GIP: lower for PMP ($P=0.001$)	Insulin, GLP-1, PYY and appetite scores similar between meals; Lower GIP for PMP; incretin linked to adipose tissue TAG absorption	Alyami et al. (2019)

Single-blind RCT crossover	Healthy adults (n=15); Prediabetes (n=14)	Finger millet muffin vs matched wheat muffin	Single meal; Glycaemic response (GR) & insulin response (IR) over 3h; Gastric emptying (GE) & satiety over 4h	GR peak significantly lower for millet muffin (P=0.013); IR iAUC at 180 min: significant group x muffin interaction (P=0.042) - reduced in prediabetics only; GE ascension time Tasc: significant interaction (P=0.017)	No significant effect on satiety AUC; Slower gastric emptying for millet muffin in prediabetics; Polyphenols and fibre proposed as mechanistic drivers	Almaski et al. (2022)
GI determination + dietary intervention	Healthy subjects (GI testing); Prediabetic subjects (intervention)	Millet-based food mix (protein: 19.41 g/100g; fibre: 21.11 g/100g) formulated as: - Roti - Dosa - Mudde (dumpling)	Acute single meal for GI testing; Dietary intervention duration not explicitly stated	GI: dosa=37 (low); mudde=48 (low); roti=53 (low); GL: 11.05, 18.43, 18.09 (moderate); FBS: 120.50+/- 18.73 to 97.81+/- 20.00 mg/dL; HbA1c: 6.14+/- 0.30 to 5.67+/-0.40% (after intervention)	Good sensory acceptance of all three preparations, comparable to regional standards; High dietary fibre content supports slow digestion and glucose absorption	Geetha et al. (2020)
Acute GI determination study	Healthy male and female subjects	Dambu (traditional Nigerian meal) from: - Pearl millet vs - Maize; enriched with beans, groundnut,	Acute single meal; Blood glucose over standard GI testing protocol	Female: millet Dambu BG = 5.14+/- 0.53 (vs maize 5.2+/- 0.8); Male: millet Dambu BG = 4.94+/- 0.9;	Sensory preference favoured maize Dambu in flavour, taste, texture and colour; Significant sensory difference	Aliyu et al. (2020)

		vegetables		Maize Dambu GI: females 41.51%; males 40.33%; Both products in low GI range	between preparations ($p < 0.05$)	
Self-controlled clinical trial (free-living)	Subjects with impaired glucose tolerance (IGT)	50 g/day whole foxtail millet added to habitual free-living diet	12 weeks; Assessments at weeks 0, 6, 12; clinical parameters investigated	FBG: 5.7+/-0.9 to 5.3+/-0.7 mmol/L ($p < 0.001$); 2h postprandial glucose: 10.2+/- 2.6 to 9.4+/-2.3 mmol/L ($p = 0.003$); Insulin resistance decreased ($p = 0.007$); Sex-dependent differences in glucose-lowering effect observed	Serum leptin significantly increased ($p = 0.012$); Marginal reduction in systemic inflammation; Foxtail millet has relatively low starch digestibility and moderate GI	Ren et al. (2018)
Controlled human clinical trial	Type 2 diabetes mellitus (T2DM); n=100	Multigrain millet-based flatbread vs control diet	Pre-post comparison; specific duration not stated in abstract	FBG: no significant decrease (140.70+/-8.43 vs 132.89+/- 5.63 mg/dL); Insulin: significantly decreased (12.96+/-1.06 vs 10.83+/-1.03 microIU/mL); HbA1c: significantly decreased (8.01+/-0.27 vs 7.40+/- 0.21%); Insulin resistance decreased	LDL significantly decreased (116.0+/-5.67 vs 98.7+/-5.68 mg/dL); Systolic & diastolic BP significantly decreased; TG and VLDL increased; HDL unchanged; RBP4 and hs- CRP unchanged	Sobhana et al. (2020)
24-week	Healthy adults;	12 types of	Acute: single	All FMP: low GI	PAC increased	Kumari et

randomised crossover + acute GI study	n=18 (crossover); separate cohort for acute GI testing	finger millet porridge; processing variables: - Milling - Parboiling - Steaming (15min) - Particle size	meal for GI; Long-term: 24-week randomised crossover	(<55) except raw roasted flour (medium-high GI); Parboiled + 15-min steaming: lowest GI; PAC: +23% (TEAC) and +14% (FRAP) at 2h post-meal; No significant change in plasma glucose or TC at 24 weeks	after 8 weeks vs baseline (FRAP & TEAC); Phenolic content and antioxidant activity varied substantially by processing; Parboiling + steaming preserved most polyphenols	al. (2020)
Controlled dietary supplementation study	Type 2 diabetic subjects; n=15	65 g/day resistant starch (RS)-rich broken sorghum (rawa/RS-rich millet food)	90 days; pre-post measurements	FBG: significantly reduced ($p<0.05$); HbA1c: non-significant reduction; eAG: non-significant reduction; TC and LDL-C: significantly reduced ($p<0.05$); TG, HDL-C, VLDL-C: non-significant changes	BMI significantly reduced ($p<0.05$); RS acts similarly to dietary fibre without altering sensory properties; Small sample (n=15) limits generalisability	Hymavathi et al. (2020)
Single-arm real-world observation (hospital registry)	Type 2 diabetes (T2DM); n=60 (from 65; 5 excluded)	Millet-based functional food diet: 60% millets 20% soya bean 10% brown rice 8% peanuts 2% flaxseeds; Daily millet intake	12 weeks; Dietary, clinical and physical activity data by validated questionnaires; BP by sphygmomanometer	Significant decline in fasting and 2h postprandial blood glucose; Significant reduction in HbA1c; TC, VLDL and TG significantly	CRP, TNF-alpha, IL-6 significantly reduced; Oxidative stress markers (TBARS, MDA, diene conjugates) reduced; Antioxidant	Singh et al. (2020)

		increased ~11-fold (21 to 235 g/day)		reduced; Systolic and diastolic BP significantly reduced	vitamins A, E, C, beta- carotene increased; Females: Hb, serum Ca, Mg significantly increased	
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Abbreviations: iAUC, incremental area under the curve; GI, glycaemic index; GL, glycaemic load; FBG, fasting blood glucose; BG, blood glucose; HbA1c, glycated haemoglobin; TC, total cholesterol; LDL-C, low-density lipoprotein cholesterol; HDL-C, high-density lipoprotein cholesterol; TG, triglycerides; VLDL, very low-density lipoprotein; GIP, glucose-dependent insulinotropic polypeptide; GLP-1, glucagon-like peptide 1; PYY, peptide YY; TAG, triacylglycerol; PAC, plasma antioxidant capacity; TEAC, trolox equivalent antioxidant capacity; FRAP, ferric ion reducing antioxidant power; BMI, body mass index; BP, blood pressure; CRP, C-reactive protein; TNF, tumour necrosis factor; MDA, malondialdehyde; TBARS, thiobarbituric acid reactive substances; eAG, estimated average glucose; FMP, finger millet porridge; PMP, pearl millet porridge; SOP, Scottish oats porridge; IGT, impaired glucose tolerance; T2DM, type 2 diabetes mellitus; RS, resistant starch; Hb, haemoglobin; Ca, calcium; Mg, magnesium; RCT, randomised controlled trial; VAS, visual analogue scale.

Geetha et al. (2020) evaluated a traditional millet-based food mix with high protein (19.41 g/100 g) and dietary fibre content (21.11 g/100 g), formulated as three traditional preparations: roti, dosa, and mudde. Glycaemic index values were 37 for dosa, 48 for mudde, and 53 for roti, all within the low GI classification (< 55), with glycaemic loads of 11.05, 18.43, and 18.09, respectively. All preparations demonstrated good sensory acceptance comparable to regional standards. A dietary intervention in prediabetic subjects demonstrated a significant reduction in fasting blood glucose (from 120.50 ± 18.73 to 97.81 ± 20.00 mg/dL) and HbA1c (from 6.14 ± 0.30 to $5.67 \pm 0.40\%$), highlighting clinically meaningful improvements achievable through regular incorporation of millet-based preparations into the diet.

Ren et al. (2018) conducted a 12-week self-controlled clinical trial in free-living subjects with IGT, supplementing the habitual diet with 50 g per day of whole foxtail millet. Assessments at weeks 0, 6, and 12 revealed that mean fasting blood glucose declined significantly from 5.7 ± 0.9 to 5.3 ± 0.7 mmol/L ($p < 0.001$), and 2-hour postprandial glucose fell from 10.2 ± 2.6 to 9.4 ± 2.3 mmol/L ($p = 0.003$). These glycaemic improvements were accompanied by a significant decrease in insulin resistance ($p = 0.007$) and a significant increase in serum leptin ($p = 0.012$), potentially reflecting enhanced satiety signalling. A

marginal reduction in systemic inflammation was also noted. Importantly, a sex-dependent difference in the glucose-lowering response to foxtail millet was observed, warranting further investigation into whether metabolic responses vary by biological sex.

Aliyu et al. (2020) assessed the glycaemic index of Dambu, a traditional Nigerian meal prepared from pearl millet or maize enriched with beans, groundnuts, and vegetables, in healthy male and female subjects. In female subjects, pearl millet Dambu was associated with a lower blood glucose response (5.14 ± 0.53) compared to the maize preparation (5.2 ± 0.8). Both products were within the low GI range, supporting pearl millet Dambu as a suitable food option for blood glucose management. Sensory evaluation, however, favoured the maize version in overall acceptability across flavour, taste, texture, and colour, highlighting a common tension between metabolic benefits and consumer preference that must be addressed in any dietary implementation strategy.

Several clinical studies have examined the effects of millet-based dietary patterns in patients with established T2DM, with outcomes extending beyond glycaemia to include lipid profiles, blood pressure, systemic inflammation, oxidative stress, and micronutrient status. Sobhana et al. (2020) conducted a clinical trial in 100 type 2 diabetic participants comparing a multigrain millet-based

flatbread to a control diet. While fasting blood glucose did not decline significantly, insulin levels fell significantly (12.96 ± 1.06 vs. 10.83 ± 1.03 microIU/mL) and HbA1c improved significantly (8.01 ± 0.27 vs. $7.40 \pm 0.21\%$), indicating improved long-term glycaemic control and insulin sensitivity. LDL cholesterol declined substantially (116.0 ± 5.67 vs. 98.7 ± 5.68 mg/dL), and both systolic and diastolic blood pressure decreased significantly following the intervention. These cardiometabolic improvements are of considerable clinical relevance given the markedly elevated cardiovascular risk that accompanies T2DM. Notably, total cholesterol, RBP4, and high-sensitivity CRP remained unchanged, suggesting the lipid-lowering effects were selective.

Singh et al. (2020) reported a real-world hospital registry observation in 60 type 2 diabetic subjects administered a millet-based functional food diet (millets 60%, soya bean 20%, brown rice 10%, peanuts 8%, flaxseeds 2%) for 12 weeks, with daily millet intake increasing approximately 11-fold over the intervention period. Significant reductions were observed in fasting and two-hour postprandial blood glucose and HbA1c. Total cholesterol, VLDL cholesterol, and triglycerides declined significantly from baseline. The intervention was additionally associated with meaningful reductions in pro-inflammatory cytokines (CRP, TNF-alpha, and IL-6), and in markers of oxidative stress (TBARS, MDA, and diene conjugates), while antioxidant vitamins A, E, C, and beta-carotene increased. In female participants, haemoglobin, serum calcium, and magnesium levels rose significantly, suggesting that a millet-rich diet may simultaneously address micronutrient deficiencies commonly encountered in T2DM. The approximate 11-fold increase in daily millet intake underscores the importance of dose in mediating these wide-ranging metabolic effects.

Hymavathi et al. (2020) investigated resistant starch (RS)-rich broken sorghum supplementation at 65 g per day for 90 days in 15 diabetic subjects. Significant reductions were recorded in BMI, fasting glucose, total cholesterol, and LDL cholesterol ($p < 0.05$). Reductions in HbA1c,

estimated average glucose, and triglycerides did not reach statistical significance, likely attributable to the small sample size and study duration. The physiological properties of resistant starch, which behaves analogously to dietary fibre in slowing glucose absorption without substantially altering sensory characteristics, are proposed as the primary mechanism underpinning these effects.

An important and often underappreciated dimension of millet clinical research concerns how food processing modulates glycaemic and nutritional outcomes, given that traditional and contemporary preparation methods vary widely across regions and cultures. Kumari et al. (2020) systematically evaluated 12 types of finger millet porridge prepared under different conditions, including variations in milling, parboiling, steaming duration, and particle size, measuring GI, glycaemic load, phenolic content, antioxidant activity, and plasma antioxidant capacity (PAC) in 18 healthy adults in a 24-week randomised crossover study. Nearly all porridges exhibited low GI values below 55, with the notable exception of raw roasted flour preparations, which produced medium to high GI responses for both fine and coarse particle sizes. Parboiling finger millet grains with 15 minutes of steaming emerged as the optimal processing condition, producing porridges with both low GI and high plasma antioxidant capacity. Short-term consumption elevated PAC by 23% as measured by TEAC and by 14% as measured by FRAP within two hours. After 8 weeks of regular consumption, PAC had increased further from baseline values. These findings demonstrate unequivocally that not all millet preparations are glycaemically equivalent, and that processing choices significantly modulate both the glycaemic and antioxidant properties of millet-based foods.

Such bioactive compounds promote antioxidant, anti-inflammatory, and antidiabetic effects through improved glucose metabolism and enhanced β -cell function. FMP-60 displayed a sturdy ability to stimulate GLP-1 secretion from intestinal L-cells in vitro and in diet-caused obese mice. Risen endogenous GLP-1 levels were linked to improved glucose homeostasis, decreased

hyperlipidaemia, and inhibition of weight gain. Foxtail millet is high in dietary fiber, minerals, and polyphenolic compounds that reveal hypoglycaemic (type 2 diabetes) and hypolipidemic (obesity) properties (Yuxuan et al., 2023). Modified cereal brans (MCBs) formulated using finger millet, kodo millet, and rice bran via chemo-enzymatic processing were assessed for their protective effects against high-fat diet (HFD) produced obesity. The study revealed that supplementation with MCBs diminished body weight gain, improved glucose homeostasis, reduced inflammation, improved gut health by reduction in the firmicutes/Bacteroidetes ratio and increased SCFA production, and avoided liver dyslipidemia and visceral adipose tissue hypertrophy in C57BL/6 mice (Devi et al., 2023).

5. Future Directions

The anti-diabetic action of millets is best understood not as a single-mechanism phenomenon but as a network-level intervention that simultaneously addresses carbohydrate digestion, insulin signalling, hepatic glucose production, β -cell viability, inflammation, oxidative stress, hormonal balance, and microbial ecology. This pleiotropy is a direct consequence of the diverse phytochemical landscape of millet grains, including phenolic acids, flavonoids, dietary fibers, resistant starches, bioactive peptides, and minerals such as magnesium that itself co-factors in over three hundred enzymatic reactions relevant to glucose metabolism (Tripathi et al., 2021; Mohapatra et al., 2019). Clinical translation, however, remains uneven; while several small to moderately sized trials demonstrate reductions in fasting blood glucose, glycated haemoglobin, and lipid parameters following millet-based interventions (Hymavathi et al., 2020; Ren, Yin, et

al., 2018). The heterogeneity in millet variety, processing methods, dosage, and trial duration continues to limit definitive meta-analytic conclusions. Future research should prioritize standardized characterization of millet preparations, mechanistic clinical trials incorporating biomarker panels for inflammation and microbiota composition, and head-to-head comparisons with established anti-diabetic agents to delineate the precise role of millets within integrative diabetes management.

6. Conclusion

Millets represent a nutritionally exceptional, environmentally sustainable, and clinically relevant dietary resource for the management and prevention of T2DM. Their superior content of dietary fiber, resistant starch, high-quality protein, essential micronutrients, and diverse bioactive phytochemicals underpins a multi-mechanistic anti-diabetic activity that encompasses enzymatic inhibition, insulin sensitization, gut microbiome modulation, and suppression of oxidative stress and inflammation. Clinical evidence, while still growing and in need of larger-scale validation, consistently supports the glycemic benefits of millet-based dietary substitutions in both healthy individuals and those with established T2DM. In an era defined by the convergence of a global diabetes epidemic, climate change, and the need for sustainable food systems, millets stand at a compelling intersection of nutritional science, public health, and environmental stewardship. Deliberate efforts to advance millet research, improve food product development, and integrate these crops into clinical dietary recommendations and national food policy represent a high-value, low-regret investment in global health and food sustainability.

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