

Fermented African Cereals as Functional Foods for Diabetes Management: A Review of Mechanisms, Biochemical Effects, and Therapeutic Potential

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ABSTRACT

Diabetes mellitus is a growing global health crisis, with over 537 million adults affected worldwide. The search for affordable, culturally relevant dietary solutions has directed attention toward traditionally fermented African cereals, particularly acha (*Digitaria exilis*), finger millet (*Eleusine coracana*), and pearl millet (*Pennisetum glaucum*), which are known for their rich nutritional profiles and bioactive constituents. This review examines the scientific evidence supporting the use of these three fermented African cereals as functional foods for the prevention and management of diabetes mellitus. A narrative review of the published literature was conducted. A systematic search was performed across Google Scholar, PubMed, and Scopus, yielding 284 articles after initial screening; 195 were assessed on abstract review, 112 on full-text review, and 87 were included in the final synthesis. Inclusion and exclusion criteria are detailed in the Methodology section. Sources spanned peer-reviewed studies of cereal fermentation, biochemical changes, antidiabetic mechanisms, alloxan-induced animal models, and key biochemical markers of diabetes. Fermentation significantly modifies the carbohydrate, protein, lipid, and phenolic profiles of these cereals, reducing antinutritional factors and enhancing the bioavailability of health-promoting compounds. These changes result in lower glycaemic indices, improved inhibition of digestive enzymes such as alpha-amylase and alpha-glucosidase, enhanced antioxidant activity, and beneficial modulation of gut microbiota. Evidence from in vitro and animal model studies indicates that fermented acha, finger millet, and pearl millet may improve blood glucose control, lipid profiles, liver function, and oxidative stress markers in diabetic conditions. Fermented acha, finger millet, and pearl millet show considerable promise as functional foods for diabetes management. However, the current evidence base rests almost entirely on in vitro and animal studies. The absence of human clinical trial data is the most critical limitation of the existing literature and constitutes the most urgent research priority. Incorporating these traditionally available cereals into dietary strategies could provide a low-cost, culturally appropriate complement to conventional diabetes treatment, particularly in sub-Saharan Africa, once confirmed by well-designed randomized controlled trials.

KEYWORDS: Diabetes Mellitus, Fermented Cereals, Acha, Finger Millet, Pearl Millet, Functional Foods, Glycaemic Control, Alloxan-induced Diabetes, Antidiabetic, Africa

I. INTRODUCTION

Diabetes mellitus is one of the most serious and rapidly growing non-communicable diseases globally. It is a long-term metabolic condition in which the body is unable to properly regulate blood glucose levels, either because the pancreas does not produce enough insulin or because the body cannot use insulin effectively (American Diabetes Association Professional Practice Committee, 2022). The consequences are wide-ranging and severe: diabetes is a leading cause of blindness, kidney failure, heart disease, stroke, and limb amputation. A person somewhere in the world dies from diabetes-related complications every five seconds (American Diabetes Association [ADA], 2024). In 2021, an estimated 537 million adults were living with diabetes globally, and this number is projected to rise to 783 million by 2045 (International Diabetes Federation [IDF], 2023). The financial burden is equally formidable: global spending on diabetes management has surpassed \$966 billion per year, placing enormous strain on healthcare systems, particularly in low- and middle-income countries (Alleyne & Zvorygina, 2024). In Africa, where many healthcare systems face significant resource constraints, the rising prevalence of diabetes constitutes a particularly urgent public health challenge.

In response to this crisis, there is growing scientific interest in the potential of traditional foods to complement or reduce dependence on pharmaceutical interventions. Cereals indigenous to Africa, particularly acha (*Digitaria exilis*), finger millet (*Eleusine coracana*), and pearl millet (*Pennisetum glaucum*), have attracted attention for their unique nutritional profiles. These grains are rich in dietary fibre, essential minerals, phenolic compounds, and bioactive substances that may support metabolic health (Allai et al., 2022; Owusu-Kwarteng et al., 2024). Fermentation is one of the oldest food processing methods known to humanity and remains widely practiced across African communities. Microbial activity during fermentation transforms the chemical composition of cereals, enhancing nutritional quality, improving digestibility, reducing harmful antinutrients, and producing new bioactive compounds (Fusco et al., 2017; Tamang et al., 2016). Recent evidence suggests that fermented cereals may positively influence glucose metabolism, inhibit key digestive enzymes linked to blood sugar spikes, and reduce oxidative stress, all of which are directly relevant to diabetes management (Pei et al., 2022; Kaur et al., 2024).

Despite this emerging body of evidence, scientific information specifically comparing the effects of fermented acha, finger millet, and pearl millet on diabetes-related biochemical parameters remains scarce. Much of the existing research relies on *in vitro* tests or limited animal studies, and there is a pressing need for systematic reviews that synthesize available knowledge and identify gaps. This review seeks to address that need by synthesizing evidence on the nutritional composition of these three cereals, the biochemical changes induced by fermentation, the mechanisms by which fermented cereals may exert antidiabetic effects, and the relevance of alloxan-induced diabetic animal models for evaluating these effects. The review also discusses key biochemical markers of diabetes that are most relevant for assessing dietary interventions and critically differentiates the strength of evidence from *in vitro*, animal, and human studies throughout.

II. RELATED WORKS

A. Nutritional Profiles of Acha, Finger Millet, and Pearl Millet

The nutritional profiles of the three target cereals are summarized in Table 1, which provides a comparative overview prior to fermentation. Acha (*Digitaria exilis*), also known as fonio, is an ancient West African cereal cultivated for thousands of years, particularly in the Sahel region.

Despite its long history, it remains among the least-studied cereals (Zhu, 2020). Acha is notable for its protein content (7-12%) and for being rich in the essential amino acids methionine and cysteine, which are often deficient in other cereals (Jideani, 2012; Shuluwa et al., 2021). It also provides significant iron, calcium, and B-group vitamins. Crucially for diabetes management, acha has been reported to have a low glycaemic index, and its dietary fibre content may slow glucose absorption and promote satiety (Obloh et al., 2015).

Table 1: Comparative Nutritional Profiles of Acha, Finger Millet, and Pearl Millet Prior to Fermentation

Cereal	Protein (g/100g)	Dietary Fibre (g/100g)	Calcium (mg/100g)	Iron (mg/100g)	Key Phenolic Compounds	GI (approx.)	Key Reference
Acha (Digitaria exilis)	7.0-12.0	3.3	44	8.5	Phenolic acids, flavonoids	Low (<55)	Jideani (2012); Shuluwa et al. (2021)
Finger Millet (Eleusine coracana)	7.0-12.0	11.5-20.0	344	3.9-4.6	Catechins, ferulic acid, tannins	Low-Medium (55-69)	Puranik et al. (2017); Chaudhary et al. (2023)
Pearl Millet (Pennisetum glaucum)	8.0-19.0	8.5	42	4.7-6.5	Ferulic acid, catechins, flavonoids	Low-Medium (55-70)	Anitha et al. (2021); Sheoran et al. (2024)

GI = Glycaemic Index; approx. = approximate. Values represent ranges from the literature.

Finger millet (*Eleusine coracana*) is remarkable for its exceptionally high calcium content, which can reach 344 mg per 100 g, up to ten times higher than many other cereals, making it particularly valuable in populations with limited dairy access (Puranik et al., 2017; Gupta et al., 2017). Its dietary fibre content (15-20% of grain weight) is among the highest of any cereal. Finger millet contains phenolic compounds, including flavonoids and phenolic acids, associated with antioxidant and hypoglycaemic properties (Devi et al., 2014; Kumar et al., 2016). Several studies have demonstrated its capacity to inhibit carbohydrate-digesting enzymes (Chaudhary et al., 2023), though the magnitude of this effect varies considerably across studies, likely reflecting differences in variety, growing conditions, and analytical methods.

Pearl millet (*Pennisetum glaucum*) is a drought-tolerant staple in arid and semi-arid regions of Africa and Asia (Abubakar et al., 2023). It provides iron (4.7-6.5 mg per 100 g), zinc, and B-complex vitamins relevant to anemia prevention (Sheoran et al., 2024). Its phenolic compounds confer antioxidant properties (Shahidi et al., 2021), and its protein content (8-19%), relatively good essential amino acid profile, and lower glycaemic index compared to wheat and white rice position it as a promising grain for diabetes-friendly diets (Anitha et al., 2021; Agrawal et al., 2023). It should be noted, however, that GI values for all three cereals vary substantially across studies depending on processing method, variety, and the reference food used in GI determination.

B. Fermentation and Its Effects on Cereal Biochemistry

Cereal fermentation is a complex biochemical process driven primarily by lactic acid bacteria (LAB), including species of *Lactobacillus*, *Pediococcus*, *Leuconostoc*, and *Weissella*, as well as yeasts, particularly *Saccharomyces cerevisiae* (Ruiz-Rodriguez et al., 2017; Nout, 2009). These microorganisms metabolize carbohydrates and other nutrients, producing organic acids, enzymes, and bioactive compounds. Fermentation can be spontaneous, relying on naturally occurring microflora, or controlled, using specific starter cultures (Holzapfel, 2002). A critical limitation of the existing literature is the substantial variability in fermentation outcomes across studies. The specific LAB strains present during spontaneous fermentation differ markedly by region, season, and substrate, which profoundly influence the phenolic profile, organic acid concentration, and enzyme-inhibitory capacity of the final product. Fermentation duration is equally important: studies have shown that the content of bound phenolics in finger millet increases significantly over 48-72 hours of fermentation but may plateau or decline thereafter, suggesting an optimal window that is not consistently defined across the literature (Bangar et al., 2022). Environmental conditions, including temperature, humidity, and substrate moisture content, further modulate microbial community composition and metabolic output. This variability complicates direct comparisons between studies and underscores the need for standardized fermentation protocols in future research.

Among the most important biochemical changes during fermentation is the breakdown of complex carbohydrates by amylolytic enzymes, thereby reducing starch content and increasing the levels of simpler sugars and organic acids (Nkhata et al., 2018). Protein hydrolysis improves protein digestibility (Sa et al., 2020). Fermentation also activates endogenous phytases that degrade phytic acid, a major antinutritional compound that binds minerals and reduces their absorption (Pramitha et al., 2021), thereby potentially improving mineral bioavailability. The transformation of phenolic compounds during fermentation is particularly relevant to diabetes, as fermentation increases the solubility and bioavailability of phenolic acids and flavonoids, enhancing antioxidant activity (Chandrasekara & Shahidi, 2012). Short-chain fatty acid (SCFA) production during fermentation has also been linked to improved insulin sensitivity and glucose homeostasis (Ai et al., 2021). Table 2 summarizes these key biochemical changes across the three target cereals.

Table 2: Summary of Key Biochemical Changes Induced by Fermentation in Acha, Finger Millet, and Pearl Millet

Biochemical Parameter	Acha	Finger millet	Pearl millet	References
Starch content	Reduced	Reduced	Reduced	Nkhata et al. (2018); Adebisi et al. (2016)
Phytic acid	Reduced	Substantially reduced	Reduced	Jan et al. (2022); Pramitha et al. (2021)
Protein digestibility	Improved	Significantly improved	Improved	Mitharwal et al. (2021); Sa et al. (2020)
Phenolic bioavailability	Increased	Increased (bound phenolics)	Increased	Chandrasekara & Shahidi (2012);

Antioxidant activity	Enhanced	Enhanced	Enhanced	Bangar et al. (2022) Pei et al. (2022); Kaur et al. (2024)
Alpha-amylase inhibition	Increased (indirect)	Significantly increased	Significantly increased	Bangar et al. (2022); Pei et al. (2022)
Glycaemic response	Lowered	Lowered	Lowered	Ansari & Pourjafar (2022); Poutanen et al. (2009)

SCFA = Short-chain fatty acids. Changes reflect general trends reported in the literature; magnitude varies with fermentation conditions.

C. Mechanisms of Antidiabetic Action of Fermented Cereals

Several interrelated mechanisms have been proposed to explain how fermented cereals may support diabetes management. These are depicted conceptually in a graphical abstract submitted as a supplementary file. First, fermentation modifies starch structure and digestibility. The formation of resistant starch and the acidification of the food matrix by lactic and acetic acids slow gastric emptying and reduce the rate of carbohydrate digestion, resulting in a lower glycaemic response (Poutanen et al., 2009; Ansari & Pourjafar, 2022). This effect is directly beneficial for people with diabetes, who need to limit rapid postprandial glucose excursions. Second, fermented cereals are rich in bioactive compounds, including phenolic acids, flavonoids, and bioactive peptides, that inhibit alpha-amylase and alpha-glucosidase, enzymes that catalyze the digestion of dietary starches and their conversion to absorbable glucose. Inhibiting both enzymes slows glucose release into the bloodstream. Pei et al. (2022) demonstrated strong inhibition of both enzymes in fermented pearl millet preparations, while Kaur et al. (2024) reported significant improvements in in vitro postprandial glucose regulation in fermented finger millet linked to enhanced antioxidant activity. It is important to note, however, that in vitro enzyme inhibition assays do not necessarily predict in vivo efficacy, as the stability and bioavailability of inhibitory compounds under gastrointestinal conditions remain incompletely characterized.

Third, fermented cereals may positively modulate the gut microbiota. The gut microbiome plays a critical role in glucose homeostasis, and dysbiosis has been linked to insulin resistance and metabolic disorders (Sanlier et al., 2019). Prebiotic fibres, exopolysaccharides, and organic acids produced during fermentation can selectively promote the growth of beneficial bacteria, potentially improving metabolic outcomes (Jeyaraman et al., 2024). Fourth, fermentation enhances the solubility and activity of antioxidant compounds, which may help combat the elevated oxidative stress central to diabetes progression (Roasa et al., 2021). Taken together, these mechanisms provide a plausible, biologically coherent basis for the antidiabetic effects of fermented cereals. However, it should be emphasized that the hierarchy of evidence supporting each mechanism differs substantially. Enzyme inhibition is supported by multiple in vitro studies; gut microbiota modulation is largely inferential in the cereal fermentation literature and has not been directly demonstrated for these three cereals in controlled trials. Clinical translation of these mechanisms remains an urgent area for investigation.

D. Alloxan-Induced Diabetes as an Experimental Model

The alloxan-induced diabetic rat model is one of the most widely used tools for studying diabetes and testing potential antidiabetic interventions. Alloxan selectively destroys insulin-producing beta cells in the pancreas by generating reactive oxygen species, inhibiting glucokinase, and disrupting intracellular calcium balance, ultimately leading to beta cell death and insulin-deficient hyperglycaemia (Szkudelski, 2001; Mabhida et al., 2018; Benakova & Plecita, 2021). This model offers practical advantages for food science research: it is reproducible, relatively rapid to establish, and produces metabolic derangements, including hyperglycaemia, dyslipidaemia, and oxidative stress, that parallel key features of type 1 diabetes and can partially model aspects of advanced type 2 diabetes (de-Almeida et al., 2020; Luka et al., 2017; Saini & Mazumber, 2024). However, the model has important limitations that must be explicitly acknowledged. The alloxan model lacks the autoimmune component characteristic of human type 1 diabetes and the progressive insulin resistance that underlies type 2 diabetes. Alloxan may also cause non-specific damage to tissues expressing the GLUT2 transporter, including the liver and kidneys (Noor, 2023; Rees & Alcolado, 2005). Furthermore, the metabolic response to dietary interventions in alloxan-diabetic rodents may not reliably predict outcomes in humans, given differences in gut microbiota composition, metabolic rate, and disease pathophysiology. Caution is therefore warranted in extrapolating animal model findings to clinical recommendations.

E. Key Biochemical Parameters in Diabetes Research

Evaluating the effects of fermented cereals on diabetes requires careful measurement of a range of biochemical markers. Blood glucose levels are the primary indicator of glycaemic status, with fasting and postprandial measurements providing direct evidence of glycaemic control (Kowalski & Bruce, 2014). Glycated haemoglobin (HbA1c) reflects average blood glucose over two to three months and is widely used as both a diagnostic and monitoring tool (Krhac & Lovrencic, 2019). Serum insulin levels and the Homeostatic Model Assessment of Insulin Resistance (HOMA-IR) assess insulin secretion and sensitivity (Chevrier et al., 2016). Lipid profiles, including total cholesterol, triglycerides, LDL cholesterol, and HDL cholesterol, are critical, given the high cardiovascular risk associated with diabetes (Feingold & Grunfeld, 2023). Liver function enzymes (ALT, AST, ALP) and kidney function markers (serum creatinine, blood urea nitrogen) are monitored because both organs are frequently impaired in diabetes (Soliman et al., 2018; Jiang et al., 2024). Finally, oxidative stress markers, including malondialdehyde (MDA), superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx), and inflammatory markers such as C-reactive protein (CRP) and cytokines (TNF-alpha, IL-6) provide evidence of redox imbalance and chronic low-grade inflammation, both of which are closely intertwined with insulin resistance and diabetic complications (Martemucci et al., 2023; Paul et al., 2022).

F. Identified Research Gaps

Although a growing body of in vitro and animal evidence supports the antidiabetic potential of fermented cereals, several important gaps remain. First, there is a lack of comprehensive in vivo studies simultaneously examining multiple biochemical parameters in the context of fermented acha, finger millet, and pearl millet. Most studies have examined a limited set of outcomes or a single cereal type. Second, the specific microbial strains and fermentation conditions that optimize antidiabetic bioactivity have not been systematically characterized. Third, the histological effects of these fermented cereals on pancreatic tissue remain underexplored. Fourth, direct head-to-head

comparisons of fermented versus unfermented versions of these cereals in controlled experimental designs are limited. Finally, and most critically, there are essentially no human clinical trials involving fermented acha, and the clinical evidence for fermented finger millet and pearl millet is extremely limited, making it impossible to draw firm conclusions about translational value for human diabetes management.

III. METHODOLOGY

This study is a narrative review of the existing scientific literature on the antidiabetic potential of fermented acha, finger millet, and pearl millet. The review was conducted using a systematic search strategy across Google Scholar, PubMed, and Scopus. Search terms included combinations of the following: "fermented cereals and diabetes", "acha fonio antidiabetic", "Digitaria exilis diabetes", "finger millet Eleusine coracana diabetes", "pearl millet Pennisetum glaucum diabetes", "fermented grains blood glucose", "lactic acid bacteria cereal fermentation", "alloxan-induced diabetes animal model", "alpha-amylase alpha-glucosidase inhibition cereals", and "African cereals functional foods". The search identified 284 potentially relevant records. After removal of duplicates and screening of titles and abstracts, 195 records were assessed. Following full-text review, 112 articles met the eligibility criteria, of which 87 were ultimately included in the synthesis after quality assessment. Reasons for exclusion included: non-English language publications, absence of data on any of the three target cereals or their fermented forms, conference abstracts without corresponding full-text articles, and studies reporting only non-fermented cereal data without transferable mechanistic relevance.

Inclusion criteria for selected studies were: peer-reviewed publications in English; studies reporting nutritional composition, fermentation effects, in vitro antidiabetic assays, or in vivo animal model results related to the target cereals; and publications spanning from 2001 to 2024 to capture both foundational and recent evidence. Studies focusing exclusively on non-fermented forms were included where they provided essential nutritional or mechanistic context. Studies involving other cereals (e.g., sorghum, wheat, rice) were included only when they provided directly relevant mechanistic insights transferable to the target cereals. Review papers, book chapters, and conference proceedings were excluded unless no primary study was available on a particular topic.

The paper is explicitly positioned as a narrative review. Unlike a systematic review, the synthesis does not employ formal quality scoring tools (e.g., GRADE) or meta-analytic quantification. This is acknowledged as a limitation. Data extracted from the selected literature included: nutritional composition; types of microorganisms involved in fermentation; biochemical changes during fermentation; mechanisms of antidiabetic action; animal model outcomes; and key biochemical parameters used in diabetes assessment. Evidence was organized thematically and synthesized narratively to address the review objectives.

IV. RESULTS AND DISCUSSION

A. Nutritional Composition and Antidiabetic Relevance of Target Cereals

The nutritional analysis of the three cereals reveals profiles that are broadly favorable for diabetes management, even before fermentation. Acha provides approximately 9 g of protein per 100 g, 3.3 g of fibre, iron (8.5 mg), calcium (44 mg), phosphorus (177 mg), and zinc (3.1 mg), alongside a low reported glycaemic index (Jideani, 2012; 2021). The presence of the sulfur-containing amino

acids methionine (42 mg/100 g) and leucine (95 mg/100 g) is noteworthy, as they participate in metabolic pathways relevant to glucose homeostasis.

Finger millet stands out for its extraordinary calcium content (344 mg/100 g), high dietary fibre (11.5 g/100 g), and a rich phenolic profile including catechins and ferulic acid. This calcium content is clinically significant, as calcium homeostasis influences insulin secretion (Puranik et al., 2017; Gupta et al., 2017). Pearl millet, with its higher energy content (378 kcal/100 g), good protein (11 g/100 g), fat (4.2 g/100 g), and dietary fibre (8.5 g/100 g), provides a nutritionally dense option. Its relatively higher iron content compared to many staple grains is relevant for addressing anemia, which frequently complicates diabetes in low-income settings (Sheoran et al., 2024).

Taken together, the nutritional profiles of these cereals align with established dietary recommendations for diabetes management, which emphasize high-fibre, low-glycaemic-index foods, adequate micronutrient intake, and antioxidant-rich foods (Reynolds et al., 2024; Weickert & Pfeiffer, 2018). However, it is important to note that reported nutritional values in the literature vary substantially by variety, agronomic conditions, and analytical method, and these factors must be taken into account when interpreting cross-study comparisons.

B. Biochemical Effects of Fermentation on Target Cereals

The fermentation of these cereals induces a range of biochemical changes directly relevant to diabetes. Studies on fermented millet have reported significant reductions in starch content and concurrent increases in reducing sugars and organic acids over 72-hour fermentation periods (Adebisi et al., 2016). Protein digestibility improves markedly; Mitharwal et al. (2021) demonstrated significant *in vitro* protein digestibility gains in finger millet following lactic acid fermentation. Phytate reduction is consistently reported in studies of fermented cereals. Jan et al. (2022) documented a substantial decrease in phytate content in finger millet following lactic acid fermentation, with expected benefits for mineral bioavailability. For people with diabetes, improved absorption of zinc and magnesium is clinically meaningful because both minerals are cofactors in insulin signaling pathways and glucose transport (Dubey et al., 2020).

The transformation of phenolic compounds during fermentation is perhaps the most directly relevant change for antidiabetic activity. Chandrasekara and Shahidi (2012) reported that fermentation of pearl millet altered the phenolic compound profile and enhanced overall antioxidant activity. Bangar et al. (2022) demonstrated that fermented finger millet had a higher content of bound phenolics, correlated with greater inhibitory activity against alpha-amylase and alpha-glucosidase. However, it should be noted that the study by Bangar et al. (2022) relied primarily on *in vitro* assays, and the translation of these findings to *in vivo* glycaemic outcomes has not been directly demonstrated in this cereal. Ansari and Pourjafar (2022) confirmed a significant reduction in starch hydrolysis rate in fermented finger millet porridge compared to unfermented samples, consistent with organic acid production, starch structural modification, and enzyme inhibitor formation.

An important consideration that limits direct comparison across the studies cited above is variability in fermentation conditions. Differences in LAB strain composition, inoculum level, fermentation duration, and substrate preparation may substantially influence the phenolic profile and enzyme inhibitory capacity of the final product. Some studies report spontaneous fermentation under ambient conditions, while others use defined starter cultures under controlled temperature; the results are not directly comparable. This methodological heterogeneity represents a significant

gap in the current evidence base and underscores the need for standardized fermentation protocols in future research.

C. Evidence from In Vivo and Animal Model Studies

While *in vitro* studies provide useful mechanistic insights, *in vivo* studies, particularly those using alloxan-induced diabetic rat models, offer a more integrated picture of how fermented cereals affect the whole organism. In alloxan-induced diabetic rats, dietary interventions with fermented cereal-based products have been reported to reduce fasting blood glucose levels, improve lipid profiles, and lower oxidative stress markers compared with untreated diabetic controls (Ighodaro et al., 2017). The HOMA-IR index can also show improvement, suggesting a beneficial effect not only on blood glucose but also on insulin sensitivity. Studies specifically using fermented pearl millet have demonstrated strong inhibition of alpha-amylase and alpha-glucosidase activity in experimental settings (Pei et al., 2022). Kaur et al. (2024) confirmed that fermented finger millet enhances antioxidant properties and *in vitro* postprandial glucose regulation, findings relevant to diabetes management.

Liver and kidney function parameters warrant attention in diabetic studies because both organs are frequently damaged by chronic hyperglycaemia and oxidative stress. The potential protective effects of antioxidant-rich fermented cereals on hepatic and renal function, reflected in AST, ALT, ALP, creatinine, and BUN levels, require further systematic investigation in controlled *in vivo* models. A critical consideration in interpreting all *in vivo* findings from the alloxan model is the gap between this experimental system and human diabetes. As noted in Section 2.4, the alloxan model does not replicate the autoimmune pathogenesis of type 1 diabetes or the progressive insulin resistance of type 2 diabetes. Animals differ from humans in gut microbiota composition, metabolic rate, and drug metabolism, all of which affect the response to dietary interventions. The current animal-based evidence, therefore, provides a plausible proof of concept for the antidiabetic potential of these fermented cereals but cannot substitute for human clinical evidence. Until randomized controlled trials (RCTs) in human subjects are conducted, the clinical applicability of these findings must be regarded as preliminary.

D. Comparison with Literature, Evidence Hierarchy, and Broader Context

The findings reviewed here are broadly consistent with the wider scientific literature on fermented plant foods and metabolic health. Cereal fermentation studies involving other grains, such as sorghum, have similarly shown that fermentation reduces starch digestibility and glycaemic response (Pranoto et al., 2013). The mechanisms identified, namely enzyme inhibition, organic acid production, phenolic enhancement, and gut microbiota modulation, are not unique to African cereals but may be particularly pronounced in acha, finger millet, and pearl millet owing to their naturally higher phenolic compound and dietary fibre content relative to globally dominant refined grains.

Table 3 provides a structured summary of the evidence across the three cereals, organized by study type and strength of evidence. This summary illustrates that, while the mechanistic evidence is reasonably coherent across all three cereals at the *in vitro* level, *in vivo* animal data are limited and direct human evidence is absent. The evidence hierarchy across the three cereals is similar: *in vitro* (strong) > animal models (moderate; limited studies) > human clinical trials (absent).

Table 3. Summary of Evidence for Antidiabetic Activity of Fermented Acha, Finger Millet, and Pearl Millet by Cereal, Study Type, and Evidence Strength

Cereal	Study Type	Key Outcome	Mechanism Proposed	Evidence Strength	Reference
Acha	In vitro / Nutritional analysis	Low GI; mineral bioavailability	Fiber-mediated glucose slowing; phytate reduction	Moderate (no human trials)	Jideani (2012); Oboh et al. (2015)
Finger Millet	In vitro; animal model	Enhanced antioxidant; improved glycaemic regulation	Alpha-glucosidase inhibition; phenolic enhancement	Moderate (limited animal data)	Bangar et al. (2022); Kaur et al. (2024)
Pearl Millet	In vitro; animal model	Strong enzyme inhibition; antioxidant activity	Alpha-amylase/glucosidase inhibition; SCFA production	Moderate (no human trials)	Pei et al. (2022); Chandrasekara & Shahidi (2012)

GI = Glycaemic Index; SCFA = Short-chain fatty acids.

What distinguishes acha, finger millet, and pearl millet from other cereals in this context is their deep cultural relevance in West and East Africa, their affordability, and their resilience to harsh growing conditions, making them accessible to rural populations who bear the greatest burden of food insecurity and rising diabetes prevalence. The population groups most affected by the growing diabetes epidemic in Africa are precisely those communities where these cereals are traditional staples, suggesting that fermented forms of these grains could serve as practical, low-cost dietary interventions aligned with existing food cultures.

However, several important limitations constrain the ability to draw definitive conclusions. The majority of evidence derives from in vitro studies or animal models. Human clinical trials specifically evaluating the antidiabetic effects of fermented acha are essentially absent from the published literature, and RCT-level evidence for fermented finger millet and pearl millet is similarly scarce. Additionally, the optimal fermentation conditions to maximize antidiabetic bioactivity have not been standardized, and variability in raw material quality, growing conditions, and processing methods means that the composition of fermented products can vary substantially across studies.

V. CONCLUSION

This review has brought together evidence demonstrating that acha, finger millet, and pearl millet, three underutilized African cereals with strong nutritional profiles, are significantly transformed by fermentation in ways directly relevant to diabetes management. Fermentation enhances their antioxidant capacity, reduces antinutritional factors, improves mineral bioavailability, lowers the glycaemic index, and produces bioactive compounds that inhibit key enzymes in carbohydrate digestion. These combined effects position fermented versions of these cereals as promising functional foods for glycaemic control, lipid management, and protection against oxidative stress and inflammation in diabetes. However, the most critical limitation of the current evidence base must be clearly stated: the absence of human clinical trial data is the single greatest obstacle to translating these findings into dietary recommendations. Virtually all available evidence derives from in vitro studies or alloxan-induced animal models. While these provide a plausible

mechanistic basis and proof of concept for antidiabetic activity, they cannot substitute for evidence from well-designed randomized controlled trials in human subjects. This must be regarded as the most urgent research priority in this field. The alloxan-induced diabetic rat model, while reproducible and well-validated for screening purposes, has important limitations, including the absence of autoimmune pathogenesis and the potential for non-specific tissue damage, that limit the strength of inference that can be drawn from animal-based dietary intervention studies. Systematic *in vivo* studies that specifically compare fermented and unfermented versions of these three cereals and examine a comprehensive panel of biochemical markers are needed to fill gaps in the evidence base. From a practical standpoint, promoting the consumption of traditionally fermented forms of these cereals could represent a culturally acceptable, affordable, and nutritionally sound strategy for diabetes prevention and management in sub-Saharan Africa and beyond. To realize this potential, future work should prioritize well-designed randomized controlled trials in human subjects with pre-existing diabetes or at high risk, optimization and standardization of fermentation protocols to maximize antidiabetic bioactivity, characterization of the specific microbial strains and conditions driving optimal outcomes; and greater investment in production and processing infrastructure for these historically undervalued grains.

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