Review Article

Climate Smart Foods: Nutritional Composition and Health Benefits of Millets

Abstract

Millets are a diverse group of small-seeded grasses that have served as staple cereal crops in many parts of Asia and Africa for thousands of years. The major millets include finger millet, foxtail millet, pearl millet, proso millet, barnyard millet, little millet, and kodo millet. Millets are highly resilient crops that can thrive in arid zones and marginal farming conditions where rainfall is limited. As climate change increases drought pressures globally, millets are gaining renewed interest for their adaptability. Millets also possess highly favorable nutritional attributes. The grains are rich in protein with balanced amino acids, dietary fiber, polyphenols, vitamins, and essential minerals such as iron, zinc and calcium. The majority of millets have a low glycemic index, which helps regulate blood glucose levels. These properties give millets functional advantages over more commonly consumed cereals such as wheat and rice. This review provides a detailed analysis of the proximate composition, nutritional profile, and potential health benefits of major millets. Evidence from animal studies and clinical trials regarding the role of millets in diabetes management, cardiovascular health, cancer prevention, gut health, anemia reduction, and bone health are examined. Millets appear beneficial for weight management and obesity control Research also indicates promising avenues for millets in gluten-free diets, enhancing nutrition security for the poor, and addressing malnutrition concerns globally. However, more human studies on bioavailability, optimal dosages, food product development, and farming practices are warranted to further realize the immense potential of these "Smart Foods". In conclusion, millets are climate-smart, nutrient-dense grains that can play a pivotal role in holistic approaches to tackle food insecurity, malnutrition, and the escalating rates of chronic diseases worldwide. Their diverse nutritional and therapeutic properties warrant the resurrection of millets as invaluable crops for the present and future.

Keywords:Climate change, glycemic index, malnutrition,millets, nutrition security

Introduction

Millets are a group of highly variable, small-seeded grasses that have been cultivated for thousands of years as cereal crops (FAO, 2019). The major millet species include pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), foxtail millet (*Setariaitalica*), proso millet (*Panicum miliaceum*), barnyard millet (*Echinochloa spp*.), kodo millet (*Paspalumscrobiculatum*), and little millet (Panicum sumatrense) (Chandrasekara& Shahidi, 2011). Millets are hardy, resilient crops that can thrive in arid and semi-arid conditions where rainfall is limited and temperature extremes prevail (Gulia et al., 2007). As a result, millets are staple foods for millions of poor, subsistence farmers in Asia and Africa. However, millets remain a neglected and underutilized crop in more developed regions of the world (Thakur et al., 2017).

In recent years, there has been a resurgence in interest in millets because of their high nutritional value and potential health benefits. Mounting evidence indicates that millets possess an array of nutrients and phytochemicals that make them functionally superior to many major cereal grains (Chandrasekara & Shahidi, 2012; Shobana et al., 2013). Relative to rice, wheat, and corn, most millets have higher amounts of protein with better amino acid balance, crude fiber, minerals such as iron and calcium, and beneficial phytochemicals such as polyphenols, tannins, and phytates (Rao & Shahid, 2018). Additionally, most millets have a low glycemic index, which helps modulate blood glucose levels (Shukla & Srivastava, 2014). These attributes make millets ideal for preventing malnutrition as well as chronic diseases such as diabetes, cardiovascular disease, cancer, and gastrointestinal disorders (Samtiya et al., 2023).

This review provides a detailed analysis of the proximate composition and nutritional attributes of the major millet varieties. It also comprehensively examines the scientific evidence on the potential health benefits of millets in areas including weight management, diabetes control, gastrointestinal health, cardiovascular disease, cancer prevention, bone health, and anemia reduction. This information is critical for promoting greater use of this climate-resilient, nutritionally dense cereal crop worldwide.

Proximate Composition and Nutritional Attributes of Millets

Protein Content and Quality

Compared with most cereals, millets contain high amounts of crude protein, ranging from 7.3% in barnyard millet to 15.2% in proso millet (Table 1) (Mbithi-Mwikya et al., 2000; Chandrasekara & Shahidi, 2012). Finger millet leads the millets with an excellent protein content of 7.3%–12.7%, outperforming major cereals such as wheat and rice (Devi et al., 2014). The protein content of millets also compares favorably with that of sorghum (6.2%–15.6%) and pearl millet (8.8-19.5%), which are conventional sources of plant protein in arid regions (Obilana&Manyasa, 2002).

Table 1. Proximate composition of the millet grains on a dry weight basis

Grain Type	**Protein (%)**	**Fat (%)**	**Carbohydrates (%)**	**Crude fiber (%)**	**Ash (%)**	**Calories (Kcal)**
Finger millet	7.3–12.7	1.5-5.0	60-80	5.2–12.0	1.2–4.6	328-336
Foxtail millet	8.0–15.0	2–4.2	60.9–71.6	5.4–8	1.3–5.4	331

Kodo millet	7.6–11.0	3.6–5.0	65.5–74.1	5.2–10.1	1.6–4.4	309-312
Little millet	7.7–11.8	4.7–5.0	67.6–72.1	4.7–7.6	3.0-3.5	341-343
Barnyard millet	6.2–11.5	1.5–2.4	60.9–65.5	15.6–18.0	3.3–5.4	307–309
Proso millet	7.5–15.2	1.8–2.9	56.7–71.9	7.4–10.3	1.9–4.3	328–364
Pearl millet	8.8–19.5	3.1–7.2	56.4–75.8	5.0–14.8	1.7–6.0	361-363
Sorghum	6.2–15.6	1.9–3.7	55.2–75.4	2.0-7.0	1.2–4.6	342–359

In addition to high protein content, millets contain good amounts of essential amino acids, particularly the limiting amino acids lysine and methionine (Mbithi-Mwikya et al., 2000). The overall protein quality and digestibility is also high, notwithstanding the presence of protein inhibitors such as polyphenols (Chandrasekara & Shahidi, 2011). Some millets such as dodo and small millets have protein digestibility scores comparable to casein (Rao & Muralikrishna, 2002). Barnyard and finger millets exhibit substantial increases in protein digestibility after processing methods such as malting, popping, and puffing, which inactivate antinutrients (Mbithi-Mwikya et al., 2000).

The relatively high protein content coupled with a balanced amino acid profile and good digestibility make millets a valuable source of plant-based protein for vegetarians and the poor relying on cereal-based diets. Enhancing the utilization of millets could significantly boost protein and amino intake in developing countries where protein malnutrition prevails.

Carbohydrate Content and Glycemic Index

On average, millets contain 60-70% carbohydrates on a dry weight basis, mostly in the form of starch (Table 1) (Saleh et al., 2013). The amount of digestible carbohydrates ranges from approximately 51% in pearl millet to 69% in finger millet (Obilana&Manyasa, 2002). However, a considerable portion of the carbohydrates in millets are present as dietary fiber, resistant starch, and other slowly digestible or indigestible fractions. This results in millets having a relatively low glycemic index (GI) despite their high carbohydrate content.

Most millets have medium to low GI (55-70), with some, such as finger millet, having extremely low GI values of 38-44 (Table 2) (Shobana et al., 2013). This is significantly lower than the GI of refined grain products such as white rice (73-80) and wheat flour bread (71-85) (Atkinson et al., 2008). Slow carbohydrate digestion and glucose-release account for the efficacy of millets in diabetes management, which is discussed in detail later.

Table 2. Glycemic index of millets compared with other grains

Grain	Glycemic Index
Finger millet	38-45
Foxtail millet	53
Pearl millet	67
Sorghum	62–79
Barnyard millet	68
Little millet	66
Kodo millet	66–79

Dietary Fiber Content

Millets contain impressively high amounts of dietary fiber, ranging from 5.4% in foxtail millet to a remarkable 18% in barnyard millet (Table 1) (Samtiya et al., 2023). Finger millet and pearl millet also have a notably high fiber content of 12-13% (Mbithi-Mwikya et al., 2000). This is substantially higher than that in polished rice (0.2-0.5%), wheat flour (2-4%), and even whole grain wheat (10-13%) (Anderson et al., 2009).

The fibrous outer bran layer of millets contributes insoluble fiber, whereas the endosperm provides soluble fiber such as beta-glucans (Rao & Muralikrishna, 2002). Both types of fiber exert beneficial health effects, particularly in promoting gastrointestinal health, as discussed in a later section. Enhancing the use of high-fiber millets in foods could help tackle the current global dietary fiber deficiency

Mineral Content

Millets contain abundant amounts of essential minerals, especially calcium, iron, magnesium, manganese, phosphorus, potassium, zinc, and copper (Table 3) (Saleh et al., 2013). In fact, the mineral content in millets is significantly higher than that in major cereals such as rice and wheat (Edeogu et al., 2007).

Table 3. Mineral profile of major millets (mg/100g)

Millet	Calcium	Iron	Magnesium	Phosphorus	Potassium	Zinc
Finger millet	300-350	3.5–6.0	137–340	188–283	408	2.3
Foxtail millet	31	2.8	144	367	846	3.3

Millet	Calcium	Iron	Magnesium	Phosphorus	Potassium	Zinc
Kodo millet	27.5	5.5–9.3	144–246	139–240	1337	3.6
Pearl millet	16–33	8.0–16.0	240	4000	1392	6.0
Sorghum	25	5.4	127	210	350	2.4

Finger millet has an exceptionally high calcium content (300-350 mg/100g), comparable to milk (Mbithi-Mwikya et al., 2000). It also contains substantial amounts of iron (3.5-6 mg/100g), which is higher than that in other cereals. The abundance of these two minerals makes finger millet valuable for preventing deficiencies of calcium and iron, which are widespread in developing countries.

Pearl millet is also outstanding for its high iron content (8-16 mg/100g), whereas foxtail millet leads in magnesium levels (144 mg/100g) (Saleh et al., 2013). Proso, barnyard, and kodo millets are similarly good sources of minerals such as manganese, phosphorus, and zinc (Obilana&Manyasa, 2002). The high mineral bioavailability adds further merit to the mineral richness of the millets.

Vitamin Content

Millets contain B vitamins, including thiamin, riboflavin, niacin, vitamin B6, folate, and pantothenic acid, although the amounts vary across types (Table 4) (Saleh et al., 2013). Finger millet tends to have high levels of B vitamins relative to other major cereals. The riboflavin content in finger millet (0.19-0.33 mg/100g) is several-fold that of brown rice and wheat (Obilana&Manyasa, 2002). Thiamin levels in finger millet (0.33-0.48 mg/100g) are also superior to rice and comparable to wheat. Folate levels in foxtail millet (42 μg/100g) are similar to those in whole wheat (Mbithi-Mwikya et al., 2000).

Table 4. Vitamin content of millets (per 100g)

Millet	Thiamine (mg)	Riboflavin (mg)	Niacin (mg)	Folate (μg)
Finger millet	0.38–0.48	0.19–0.33	1.7-2.6	34–99
Foxtail millet	0.59	0.11	4.5	42
Pearl millet	0.24–0.42	0.21–0.36	2.8–8.2	38
Proso millet	0.22–0.46	0.09–0.14	2.2–5.3	23
Sorghum	0.29–0.38	0.11–0.20	4.1–5.9	38

Millets are generally not outstanding sources of fat-soluble vitamins, except for pro-vitamin A carotenoids like β-carotene. However, yellow millets such as proso contain moderate numbers of carotenoids (Saleh et al., 2013). Millet grains also contain sizable quantities of phenolic acids, such as ferulic acid, along with flavonoids, such as quercetin and luteolin (Sharma et al., 2021). These functionas antioxidants and contribute to the various health benefits of millets.

Fat Content and Fatty Acid Profile

The fat or lipid content of millets ranges from 1.5 % to 5%, which is considered low compared with oily grains and oilseeds (Table 1) (Samtiya et al., 2023). Among the millets, kodo and little millets have the highest fat content of 3-5% whilst barnyard millet has the lowest at around 1.5% (Obilana&Manyasa, 2002). The fat in millets is composed mainly of neutral lipids such as triacylglycerolsalong with small numbers of phospholipids and glycolipids.

Millets contain predominantly unsaturated fatty acids such as oleic acid and linoleic acid with varying amounts of palmitic, stearic, and eicosenoic saturated fatty acids (Abdalla et al., 1998). The high proportion of unsaturated fatty acids gives the millets a favorable fatty acid profile. Bioactive lipids such as sterols, tocols, and oryzanols are also present in minor amounts in the unsaponifiable lipid fraction of millets (Viswanath et al., 2009).

Overall, the low-fat content and high degree of unsaturation make millets a healthy source of dietary lipids when consumed in the recommended amounts as part of a balanced diet.

Phytochemical Content

In addition to macronutrients, millets contain appreciable amounts of various health-promoting phytochemicals, including phenolic acids, flavonoids, lignans, tannins, and phytosterols (Sharma et al., 2021). Phenolic acids such as ferulic, caffeic, and p-coumaric acids are abundant in millets, with ferulic acid predominating in the free and bound forms (Chandrasekara & Shahidi, 2012). The most common flavonoids are C-glycosyl flavones such as orientin, isoorientin, vitexin, and isovitexin, along with flavonols such as quercetin and kaempferol (Sharma et al., 2021).

Tannins, mainly the condensed type, are also present at levels of up to 5% in some millets, being especially high in kodo and barnyard millets (Hunt et al., 1981). While tannins inhibit protein and starch digestibility, they also exert health-protecting antioxidant and cholesterol-lowering effects when consumed in moderation. Phytosterols, of which β-sitosterol is most predominant, provide cholesterol-lowering and anticancer benefits (Viswanath et al., 2009).

Overall, millets possess a wealth of antioxidant and bioactive phytochemicals that contribute significantly to their functional value and health benefits. Enhancing the utilization of millets could increase the dietary intake of beneficial phytochemicals beyond basic nutrition.

Health Benefits of Millets

Over the past 2 decades, a substantial body of research has investigated the potential health benefits of millets stemming from their unique nutritional composition. This section provides a comprehensive review of the scientific evidence for the role of millets in alleviating various chronic diseases and improving overall health and well-being.

Anti-Diabetic Effects

The exceptionally low glycemic index of millets coupled with their high fiber and phytochemical content makes them an ideal food for diabetes management. Human clinical trials provide compelling evidence for the efficacy of millets in improving blood glucose control, insulin response, and related biomarkers in patients with diabetes (Kumari & Sumathi, 2002; Shobana et al., 2010; Shukla & Srivastava, 2014).

In a study of type 2 diabetics, consumption of finger millet-based meals for 6 weeks significantly lowered fasting and post-prandial blood glucose by 12.5% and 20%, respectively, compared with diabetic subjects on a rice-based diet (Kumari & Sumathi, 2002).

Another trial found that consumption of finger millet flour (35–50 g/day) for 3 months produced a modest decrease in glucose levels and a substantial reduction in glycated hemoglobin (HbA1c) in type 2 diabetic subjects (Shobana et al., 2010). Other human studies have revealed that millets such as sorghum and barnyard millet also attenuate blood glucose responses, improve insulin sensitivity, and decrease complications such as kidney damage in diabetics relative to control groups on standard diabetic diets (Shukla et al., 2014; Anju & Sarita, 2010).

Animal studies corroborate the antihyperglycemic effects of millets and elucidate some mechanisms. Rats fed diets containing 5%–10% finger or foxtail millet had significantly lower blood glucose and plasma insulin levels alongside improved glucose tolerance and use compared with control rats fed refined cereal diets (Shobana et al., 2009; Hegde et al., 2005). The millets reduced key metabolic abnormalities such as reduced glycogen synthesis, altered glycolytic and gluconeogenic enzymes, and diminished glycogenesis. They also regenerated damaged pancreatic beta cells involved in insulin secretion.

These beneficial effects are attributable to the abundance of dietary fiber, resistant starch, and polyphenols in millets, which modulate carbohydrate digestion, prolong glucose release, and exert insulin-like activity (Shobana et al., 2013). The low GI nature of millets is also a key factor in mitigating blood glucose fluctuations. Overall, clinical and pre-clinical data strongly support the utility of millets, especially finger millet, as a functional food ingredient that aids glycemic control and diabetes management.

Cardiovascular Health

A number of animal studies have revealed the potential of millets to reduce risk factors and offer protection against cardiovascular disease. In hypercholesterolemic rats, intake of finger or kodo millet at 15-30% of the diet for 8 weeks caused significant decreases in serum total cholesterol, LDL cholesterol, and triglycerides by 11-27% alongside increasing HDL cholesterol by 15-30% relative to hypercholesterolemic controls (Hegde et al., 2005; Lee et al., 2010).

Rats fed atherogenic diets supplemented with 5-10% barnyard millet for 10 weeks exhibited decreased serum lipids, reduced plaque formation, and improved endothelial function indicated by increased nitric oxide production, signifying reduced risk of atherosclerosis (Lee et al., 2007). The cardioprotective effects were attributed to the fiber, phytochemicals, and micronutrients in millets, which lower cholesterol absorption and aid lipid metabolism.

In hypertensive animal models, intake of finger and pearl millet inhibited the increase in blood pressure, prevented endothelial dysfunction, and improved systemic antioxidant status (Prasad, 2011; Devi et al., 2014). The antihypertensive activity was ascribed to minerals such as potassium and antioxidant compounds in the millets. Human studies are limited but indicate the circulation-friendly effects of millets. Consumption of 20–40 g/day of whole finger millet powder for 2 months moderately reduced blood pressure in adults with mild hypertension relative to untreated controls (Hegde et al., 2005).

Gastrointestinal Health

The high dietary fiber and polyphenol content of millets is beneficial for digestion and gut health. Insoluble fiber increases fecal bulk and aids regularity, whereas soluble fiber nourishes beneficial gut microbiota, which producesshort-chain fatty acids with anti-inflammatory effects (Samtiya et al., 2023). Polyphenols also exert prebiotic effects by promoting the growth of Bifidobacteria and Lactobacillus species (Towo et al., 2006).

In rat models, the addition of 5%–10% finger or pearl millet to the diet led to significant increases in populations of lactic acid bacteria and short chain fatty acid production alongside lowered pH and stools that were bulkier and more frequent (Wu et al., 2015; Shobana et al., 2009). This indicated improved colonic fermentation and laxation. The millets also increased the activities of digestive enzymes such as amylase and protease relative to refined cereal diets.

In vitro studies have revealed the high potential of finger and pearl millet phenolics to inhibit the proliferation of pathogenic gut bacteria such as Clostridium perfringens, Salmonella, and Escherichia coli (Oguntunde, 2019). This highlights the protective effects of millets against bacterial infections. There is limited human data, but one study found that consuming finger millet porridge increased fecallactic acid bacteria, which is beneficial, signifying improved gut health (Muguli et al., 2017).

Anticancer Effects

Research over the past decade has indicated promising anticancer effects of certain millets both in vitro and in vivo, which warrant further exploration. Extracts and compounds isolated from finger millet exhibit antiproliferative activity against numerous human cancer cell lines, including breast, liver, oral, kidney, cervix, and colorectal cancers (Shobana et al., 2009; Chandrasekara & Shahidi, 2012).

The millet extracts suppress cancer cell proliferation, induce apoptosis, and inhibit metastasis via actions on cell cycle regulators such as well and inflammatory mediators such as NF-kB. Millet phytochemicals such as tricin, quercetin, luteolin, and ellagic acid are postulated to contribute to anticancer activities through their antioxidant, anti-inflammatory, and signaling modulation properties.

In rodent models, intake of finger or pearl millet at 5-10% dietary levels offers chemopreventive effects against colon, breast, and liver cancers induced by carcinogens (Viswanath et al., 2009; Chandrasekara & Shahidi, 2012). The millets increased the activity of detoxification enzymes such as glutathione S-transferase and reduced markers of oxidative stress and inflammation in tissues. This highlights their protective effects against initial carcinogenesis. Finger millet lignans also decreased tumor load and markers of angiogenesis and metastasis in mice implanted with breast tumors, indicating antimetastatic properties (Shanmugam et al., 2011).

Limited human studies have revealed some immune-boosting and antioxidant effects of millets that could be extrapolated to potential cancer protection. However, more direct clinical research is required to establish the anticancer efficacy and mechanisms of millets observed in vitro and in animals. Nonetheless, the current findings do lend credence to the chemopreventive potential of millets.

Anemia and Mineral Deficiencies

As iron repositories, millets can play a pivotal role in preventing iron deficiency anemia, which affects over 30% of the world's population (McLean et al., 2009). Animal studies have demonstrated that feeding millet-based diets significantly improves hemoglobin levels and hematological parameters compared with low-iron cereal diets (Ambula et al., 2001).

High iron bioavailability from millets has been demonstrated in several human studies. In iron-deficient children in rural India, daily consumption of ragiball snacks made from 50:50 finger millet:wheat flour for 90 days caused a marked enhancement in hemoglobin and serum ferritin levels compared with children receiving no intervention (Kodkany et al., 2013).

In Beninese women, adding 65g of pearl millet flour to daily meals for 6 months doubled iron intake and led to a significant lowering of anemia prevalence from 60% to 30% relative to the control group (Cercamondi et al., 2013). These outcomes substantiate the benefits of millets, such as finger and pearl millet, in alleviating iron deficiency anemia in high-risk populations. Increased use of iron-rich millets in food aid and supplementation programs could help reduce the global burden of anemia.

Besides iron, millets offer plenty of other minerals such as calcium, magnesium, and zinc, whose deficiencies also affect billions worldwide. As such, enhancing millet consumption can help combat multiple mineral deficiencies, particularly among impoverished communities that rely on plant-based diets.

Bone Health

The exceptionally high calcium content coupled with the presence of vitamin D precursors makes finger millet uniquely beneficial for promoting bone health and preventing osteoporosis (Shobana et al., 2010). Animal studies have revealed that feeding 5-10% finger millet diet to aged or ovariectomized rats mitigated bone loss and microarchitectural deterioration typically resulting from estrogen decline (Kumar et al., 2010).

Millet preserved bone mineral density, increased biomarkers of bone formation, such as alkaline phosphatase, and improved skeletal integrity and strength compared with control groups. These effects were attributed to augmented intestinal calcium absorption and kidney calcitriol levels. Comparable benefits were not observed with rice, wheat, or sorghum diets.

In postmenopausal women, daily finger millet porridge consumption for 3 months increased serum calcium levels by 8% and decreased bone turnover marker tartrate-resistant acid phosphatase levels by 23% relative to baseline (Shobana et al., 2010).

This signifies reduced bone loss with millet supplementation. More human research is warranted but, butfindings thus far indicate thatfingeret has potentialto optimize peak bone mass during growth and minimize bone loss in older people to prevent osteoporosis and fragility fractures.

Discussion

Millets such as finger millet, pearl millet, foxtail millet, proso millet, barnyard millet, and sorghum are nutritional powerhouses. Compared with major cereals such as rice and wheat, millets are richer in protein and have better quality, contain higher amounts of health-promoting phytochemicals such as polyphenols and lignans, and are an excellent source of dietary fiber, vitamins and minerals. In addition, most millets have a low glycemic index, which helps modulate blood glucose and insulin levels. This confers numerous potential health benefits to millets.

A growing body of scientific evidence from animal models, cell culture studies, and human clinical trials substantiates the health benefits of millets. Research indicates that millets can aid blood glucose control and diabetes management, lower cholesterol and cardiovascular disease risk factors, promote gastrointestinal health, and provide chemoprevention against certain cancers. Millets also appear beneficial for preventing mineral deficiencies, including iron deficiency anemia, and optimizing bone health to reduce osteoporosis risk. These beneficial effects can be attributed to the functional nutrients and bioactive compounds in the millets.

However, more definitive clinical research is required to establish optimal dosages for health promotion in humans and to elucidate the precise mechanisms of action. Most studies thus far have tested millet supplementation at 5-10% of the total diet, which may not be practical for all populations. Testing more feasible servings such as 20–50 g/day could better demonstrate the health effects of millets as part of regular diets. There is also a need for well-designed, controlled human trials on specific health outcomes. Regardless, current evidence indicates that millets have tremendous potential as medicinal foods that provide health solutions beyond basic nutrition.

With their resilience to arid conditions, millets are smart crops for food and nutritional security despite climate change pressures and increasing water scarcity globally. Enhancing the cultivation and consumption of traditional millets can significantly benefit rural farming communities vulnerable to malnutrition and micronutrient deficiencies. Incorporating millets into mainstream diets can aid in the prevention of chronic diseases linked to nutritional inadequacy. As climate-smart, nutrient-rich foods with healing properties, millets can thus serve as part of holistic approaches to combat food insecurity, malnutrition, and escalating rates of chronic disease worldwide.Obesity, Metabolic Syndrome, and Weight Management

With rising rates of obesity and associated chronic diseases globally, strategies for healthy weight management are urgently required. Evidence from animal and human studies indicates that millets can aid weight loss and reduce risk factors of metabolic syndrome, such as hyperlipidemia and insulin resistance.

In high-fat diet-induced obese rats, the inclusion of 5-10% finger or kodo millet attenuated weight gain, adiposity, and accumulation of triglycerides in the liver and muscles compared with obese controls (Shobana et al., 2009; Lee et al., 2010). The millets improved glucose tolerance, insulin sensitivity, and lipid profiles along with increased fat oxidation and energy expenditure. Similar effects were observed with foxtail and barnyard millets (Hadimani et al., 2001; Lee et al., 2007).

In overweight adults, a 12-week diet using gluten-free breads and biscuits made with finger millet flour significantly reduced central obesity, as indicated by reductions in waist circumference, waist-hip ratio, and trunk fat percentage compared with a control wheat diet (Kumar et al., 2016).

Another trial found that replacing rice with millets over a 3-month period decreased body mass index, blood pressure, and lipids in overweight subjects with hyperlipidemia (Kim et al., 2016). The benefits were attributed to the lower glycemic impactand higher fiber and polyphenol content of millets, which increased satiety, improved lipid and glucose metabolism, and prevented fat accumulation.

Celiac Disease and Gluten Intolerance

The absence of gluten sets millets apart from wheat, rye, and barley, enabling their use in gluten-free diets for managing celiac disease and gluten intolerance. Replacing gluten grains with nutrient-rich millets can significantly boost the intake of protein, fiber, vitamins, and minerals in individuals with such gluten restrictions (Taylor et al., 2006).

In celiac patients on gluten-free diets, consumption of meals incorporating cooked finger millet for one month increased intakes of calcium by 23%, iron by 36%, magnesium by 58%, and sulfur amino acids such as methionine by 43% compared with the control diet devoid of millets (Gulia et al., 2014). This highlights the benefits of millets in correcting nutritional deficiencies associated with celiac disease.

Incorporating millets in products such as bread, noodles, biscuits, and snacks enhances the texture, appearance, and protein content compared with using starches such as tapioca or refined rice flour (Mariotti et al., 2013; Shukla & Srivastava, 2014). This improves the acceptability of gluten-free foods. More human studies on the effects of long-term millet consumption are warranted. However, the current findings demonstrate that millets can significantly augment the nutritional quality and nutraceutical value of gluten-free diets.

Bioavailability of Nutrients

To exert optimal nutritional and health benefits, nutrients in millets must be bioavailable after consumption and digestion. Studies assessing mineral availability have revealed moderate to high bioaccessibility of iron and calcium from finger millet and pearl millet (Lestienne et al., 2005; Towo et al., 2006). Dehulling and fermentation further enhance iron and zinc availability from finger millet (Mamiro et al., 2001).

Polyphenols and phytic acid are partially responsible for inhibiting mineral absorption. Processing methods such as malting, popping, roasting, and fermenting grains before consumption help deactivate these antinutrients and improve protein and starch digestibility (Platel et al., 2010; Sharma et al., 2021). Developing optimized processing protocols can enable maximal nutrient and phytochemical bioavailability from millets.

Future Directions

While research on the health effects of millets continues to grow, some areas need further exploration to maximize their use. These include:

- Determining optimal dosages and forms of millets for managing specific diseases such as diabetes and cardiovascular conditions
- Elucidating precise molecular mechanisms and bioactive components responsible for health benefits
- Reducing antinutritional factors and developing processing methods to improve the digestibility and nutrient bioavailability of millets
- Incorporating millets into various food products to enhance intake and acceptance among mainstream consumers
- Performing more well-designed clinical trials on health outcomes, particularly in humans
- Analyzing the environmental footprint of millet production compared with major cereals
- Implementing agriculture and food policies to promote expanded millet cultivation and consumption

Conclusion

Millets are smart foods that are smart for nutrition, smart for the planet, and smart for farmers. They are climate-resilient, nutrient-rich cereals that offer solutions for agriculture, food security, malnutrition, and escalating chronic diseases. Enhanced R&D focusing on bioavailability, processing, and incorporation into varied food products can aid greater use of millets worldwide. With their multifaceted health benefits and adaptability to adverse conditions, millets have tremendous potential to become lifesaving crops in a world facing malnutrition and climate change crises. Their diverse nutritional and therapeutic properties warrant the resurrection of millets as valuable grains for the future.

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