International Journal of Food Science and Nutrition
www.foodsciencejournal.com
ISSN: 2455-4898
Received: 08-12-2025, Accepted: 07-01-2026, Published: 23-01-2026
Volume 11, Issue 1, 2026, Page No. 94-99

A comprehensive review on foxtail millet

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Abstract
Millets are small-seeded cereal grains value for their nutritional richness, dietary fiber content and naturally gluten-free nature. Among them, Foxtail millet (*Setaria italica*) is an underutilized minor millet that has gained increasing attention due to its superior nutritional profile and health-promoting properties. Foxtail millet is a climate-resilient, drought-tolerant crop with high adaptability to abiotic stresses, making it a sustainable option for future food and nutritional security. Nutritionally, foxtail millet is a rich source of protein, essential amino acid, vitamins and minerals such as iron, calcium, zinc and magnesium. Also, it contains bioactive compounds like phenolic acids, flavonoids, tannins, carotenoids, phytosterols, γ-aminobutyric acid (GABA) and antioxidant peptides. The presence of bioactive constitutes contributes to multiple health benefits such as anti-diabetic, hypoglycemic, hypolipidemic, anti-inflammantory, anti-hypertensive and potential anti-cancer effects. Furthermore, the development of foxtail millet-based value-added products demonstrates the high sensory acceptability and enhanced nutritional quality. Owning to its gluten-free nature, it is suitable for individual with celiac disease. This review highlights foxtail millet as a nutritionally dense and health-enhancing cereal with potential for advanced processing techniques and extended trials to maximize its health benefits.

Keywords: Foxtail millet, bioactive compound, antioxidant activity, functional food, gluten-free nutrition, health benefits

Introduction

Millets are a varied assortment of small-seeded cereal grains from the Poaceae family, typically grown in dry and semi-arid areas of Asia and Africa. Although they have been used for a long time, millets were slowly superseded by refined grains like rice and wheat. There are several types of millets, including Sorghum (Sorghum bicolor), Pearl millet (Pennisetum glaucum), Foxtail millet (*Setaria* italica), Kodo millet (Paspalum scrobiculatum), Finger millet (Eleusine corona), Proso millet (Panicum miliaceum), little millet (Panicum sumatrense), and Barnyard millet (Echinochloa utilis). Millets are called as 'nutri-cereals' as they are storehouse of nutrients (Divya *et al.*, 2024) [7]. Nonetheless, the increasing occurrence of metabolic conditions, micronutrient shortages, and food scarcity has sparked new interest in millets.

According to 2020 production data, global output of millets stands at indicated as 89.17 million metric tons below 74.00 area of million hectares. India is the biggest global manufacturer and front-runner in production of millets accounting for 15% of the global total output together with Niger, China, Nigeria, Mali, Sudan, Ethiopia and Senegal (Kalsi *et al.*, 2023) [12]. Foxtail millet (*Setaria italic*) belongs to *Setaria* genus of Poaceae family and subfamily Panicoideae. It is also known as Italian millet and is the oldest crop in world. This crop has been cultivated for 8000 years and presently grown in semi-arid and tropical regions of Africa, Asia, Australia, South America and especially in China, India, Mali, Nigeria and Niger (Liang *et al.*, 2018) [14]. Foxtail millet is ranked as second in the world for total production of millets (Viswasri *et al.*, 2018). Foxtail millet ranks among the earliest cultivated millet and is extensively cultivated because of its brief growing season and favorable adaptation to challenging environments, owing to its resistance to drought, insect, disease, high salinity stress tolerance and low soil fertility, along with nutritional and medicinal properties and minimal input needs. India ranks as one of the top producers of foxtail millet, where it is commonly eaten as a staple or utilized in value-added items. It is known by its local names in different states of India as Kangni (Hindi), Navane (Kannada), Thinai (Tamil), Kang (Gujarati) and Rala (Marathi) (Kuldip *et al.*, 2020). In contrast to rice and wheat, foxtail millet is gluten-free, nutrient-dense whole grain filled with diverse vitamins, minerals, and elevated protein content. Its reduced glycemic index (52–68) and lack of gluten content beyond staple foods, renders it an adjunct therapy meals for individuals with diabetes and gluten sensitivity.

Foxtail millet supports the continuous release of glucose without affecting the body's metabolic processes. FM refers to also referred to as a heart-healthy diet and helps in lowering the the development of diabetes because of its elevated magnesium levels. An adequate quantity of carbohydrates, protein, fat, fiber, minerals (Phosphorous, calcium, iron, zinc, magnesium, sodium), and phytochemicals (Phenolic compounds, Ferulic acid, chlorogenic acid, and p-coumaric, flavonoids, carotenoids, tocopherol, and tocotrienol) are clearly demonstrated in FM. Foxtail millet is a great source of many useful substances in the body, like dietary fiber, bioactive peptides, proteins, minerals, amino acids, phenolic compounds, sterols, tocols, phytic acids, carotenoids, unsaturated fatty acids, and some anti-nutritive compounds. Bioactive compounds of foxtail millet are becoming important functional food ingredients. Phenolic acid in foxtail mill*et al*so has exhibit antidiabetic, antioxidant, anti-inflammatory, and antimicrobial potential, anti-proliferative effect against MDA human breast cancer and HepG2 human liver cancer cells (Donald *et al.*, 2022). In recent years, rising consumer awareness of health-enhancing foods has sparked scientific curiosity in foxtail millet. These characteristics justify it as a functional food that may aid in preventing and managing diabetes, cardiovascular diseases, obesity, and particular cancers. Researchers have been fascinated by the unique agricultural

traits of foxtail millet, its ecological advantages related to security, the financial benefits it delivers to farmers via farming, along with its beneficial effect on human health when taken directly or as segment of food products (kalsi *et al.,* 2023) [12]. It is thus essential to alter foxtail millet to enhance its processing features, and this alteration procedure will inevitably influence the nutritional elements of foxtail millet. Therefore, the current review highlights the practicality regarding nutrition, pharmacology and importance of foxtail millet as a nutrient-dense food source to be employed in the food sectors in the upcoming future.

Statistics on production and consumption trends in foxtail

India is the biggest producer and also the largest consumer of rice, wheat and various cereal grains totaling 297.5 million tons of output in 2019–2020. Due to progress in technology the yield and efficiency of these prevalent crops like rice, wheat and maize has risen, supplanting the cultivation of additional important crops including lesser millets including foxtail, Kodo, finger, and barnyard millet.

India is the biggest producer of millets in the world, producing 41% of the total millet output in 2020, according to APEDA's 2022 report. In India, most of the small millets are grown in Madhya Pradesh, which covers 32.4% of the country's total area. Then come Chhattisgarh with 19.5%, Uttarakhand with 8%, Maharashtra with 7.8%, Gujarat with 5.3%, and Tamil Nadu with 3.9%. According to the reports, it indicates that 370 metric tons of minor millets were generated in the year with a yield of 809kg/Ha (IIMR, Millet statistics). Foxtail millet exceeds other types of millet in terms of output, achieving a yield of 2166 kg per hectare.

Over the years, there has been a decrease in the usage of Foxtail millet, which can be ascribed to different reasons.

A major factor is the evolving food choices of individuals. As societies evolve and grow more advanced, globalized, there has been a transition towards processed and ready-made meals. Foxtail millet, as a conventional and lesser-known cereal in several areas, has been overlooked and overshadowed by more favored choices. The decrease in the the use of foxtail millet in recent years has been linked to shifting food choices, city development, restricted knowledge and marketing, farming methods and accessibility, insufficient infra- structure, and handling amenities, along with cultural and geographical elements.

Taxonomy, Botanical and Agronomic traits

Foxtail millet belongs to kingdom; plantae, order; Poales, family; Poaceae, subfamily; panicoideae, genus; *Setaria* and genus; *Setaria*, species; S. italica. Foxtail millet (*Setaria italica*) is a yearly grass distinguished by tiny, round to oval seeds covered by a delicate husk. The grains range in color from light brown to pale yellow based on the cultivar and cultivation conditions. The crop is suitably adapted to poor soils and shows resilience to pests, diseases, and drought conditions, rendering it a sustainable choice amid climate fluctua-tion (Gowda *et al.,* 2022) [8]. Foxtail millet grains have a moderate weight per thousand kernels, decent bulk density, and advantageous milling properties. Nonetheless, over-dehulling and polishing may lead to signifi-can't losses of bran, which is the main source of minerals and phenolic compounds (Suma and Urooj, 2012) [20].

Morphological Characteristics

Table 1: Morphological charactersitics of Foxtail millet

Characteristic	Description
Habit & Stem	Erect, annual grass with slender, leafy stems; height 1.2–2.0 m depending on variety and environment; stems smooth or slightly rough, nodes/internodes present; may tiller from the base forming multiple shoots.
Root System	Fibrous root system with many thin adventitious roots; facilitates efficient nutrient and water uptake.
Leaves	Alternate, linear-lanceolate, glabrous; 15–50 cm long, 0.5–4 cm wide; distinct midrib, serrated margins; ligule with hairs at junction of leaf blade and sheath.
Inflorescence (Panicle)	Dense, bristly panicle resembling a fox's tail; 5–30 cm long (longer in some cultivars); erect or slightly nodding; spikelets subtended by stiff bristles varying in length.
Spikelets & Flowers	Each spikelet has two florets: upper one fertile and bisexual, lower one usually sterile or male; predominantly self-pollinated.
Grains	Small caryopsis with hard, thin hull that separates easily during threshing; seed diameter ~2 mm; color varies (yellow, brown, red, black) depending on cultivar.
Maturation Period	The plant grows for 70 - 110 days and can thrive in areas with little rain and dry climates.

Phytochemical composition of foxtail millet

New techniques like HPLC-MS, GC-MS, and NMR spectroscopy have allowed for accurate measurement of the nutraceutical components in foxtail millet. Studies in metabolomics show that the phytochemical makeup of foxtail millet can change depending on the farming conditions. As more people focus on sustainable and nutritious food options, foxtail millet is becoming an important candidate for functional foods. This highlights the need for more research into its health benefits and uses in nutrition.

a. Micronutrient

Foxtail millet is a nutrient-rich grain, especially high in B-complex vitamins and essential minerals. It has a lot of B vitamins which are important for energy production and brain function. It also contains vitamin E, which acts as an antioxidant and helps keep the skin healthy and supports the immune system. These vitamins make foxtail millet useful in fighting micronutrient deficiencies, especially in areas where it is a main part of the diet (Sahoo *et al.*, 2025). The mineral content of foxtail millet is also very good. A recent study on folic acid levels in 247 types of millet from three different regions found that folic acid content ranges from 0.37 to 2.37 mg per kg. Some substances in the millet, like phytic acid and tannin, which can reduce nutrient absorption, can be greatly reduced through proper processing methods.

b. Macronutrient

Foxtail millet is a grain rich in nutrients and has a well-balanced macronutrient profile. It mainly consists of slowly

digested starches, resulting in a low glycemic index (GI), which is advantageous for managing the blood sugar levels and diabetes. It consists of roughly 60-70% carbohydrates, mainly as complex starches and dietary fiber, leading to its low glycemic index and gradual digestion, which helps with blood sugar control.

The grain contributes 10-12% protein, featuring eight of the essential amino acids (isoleucine, leucine, lysine, methionine, phenylalanine, threonine, valine and tryptophan) which are frequently scarce in other cereals (Arora *et al.,* 2023) [3]. This renders foxtail millet an important protein source, especially in vegetarian d iets. This renders it an important protein source, especially i n vegetarian meal plans. Fatty acids such as Linoleic, oleic and linolenic acids are the main unsaturated fatty acids present while palmitic and stearic acids are main saturated fatty acids present in it. Foxtail millet contains a low-fat content (2-4%) and possesses a beneficial fatty acid composition, featuring a balanced omega-3 to omega-6 fatty acid ratio (Nadeem *et al.,* 2020) [15]. The lipid component includes unsaturated fats, mainly linoleic acid (omega-6) and alpha-linolenic acid (omega-3), beneficial for heart health.

Table 2: Nutrient composition of foxtail millet

Nutrient	Component	Content
Carbohydrate	-	60 - 70 %
Protein	-	10 - 12 %
B - Complex Vitamin	Thiamine (B1)	0.59 mg/100 g (5.7 mg/kg)
	Riboflavin (B2)	0.11 mg/100 g (1.2 mg/kg)
	Niacin (B3)	3.2 mg/100 g
	Pyridoxine (B6)	0.38 mg/100 g
	Folic acid (B9)	0.37–2.37 mg/kg (avg. 1.5 mg/kg)
Fat - soluble Vitamins	Vitamin A	1.9 mg/kg
	Vitamin E	0.5 mg/100 g (43.5 mg/kg)
	β-Carotene	1.2 mg/kg
Minerals	Iron	6.3 mg/100 g
	Calcium	31 mg/100 g
	Magnesium	81 mg/100 g
	Phosphorous	290 mg/100 g
	Zinc	2.4 mg/100 g

c. Bioactive compounds

Foxtail millet serves as a rich source of bioactive components, such as polyphenols, flavonoids and tannins, which enhance is antioxidant and anti-inflammatory attributes. Research shows that foxtail millet has around 98.5 mg/100 g of total polyphenols with notable quantities of flavonoids like quercetin and kaempferol (Hutabarat and Bowie *et al.,* 2022) [11]. These substances aid in neutralizing free radicals, minimizing oxidative stress and inflammation associated with chronic illnesses such as diabetes and cancer. Moreover, tannins (approximately 0.3% to 0.6% of dry weight) found in foxtail millet shows anti-inflammatory properties boosting its functional food potential. Additionally, foxtail millet has lignans (such as secoisolariciresinol) and saponins, which provide cardioprotective and immunomodulatory advantages (Sahoo *et al.,* 2025). Lignans found in quantities of 0.5-2.0 mg/100 g, are linked to a lower risk of cardiovascular diseases because of their cholesterol reducing and anti-atherogenic properties. Saponins found in small amounts, between 0.1 and 0.3 percent, help the body's immune system work better by controlling how certain proteins called cytokines are made. They also help lower cholesterol levels, as shown in a study by Sharma (Sharma *et al.,* 2015) [19].

Phytopharmacological Properties:

a. Antioxidant activity

Foxtail millet has exceptional antioxidant properties, mainly due to its elevated levels of phenolic and flavonoid compou nds (Sharma *et al.,* 2015) [19]. Research indicates that foxtail millet has a total phenolic content varying from 168.2 to 328.5 mg GAE/100 g and a total flavonoid content of 25.4 to 58.6 mg QE/100 g, which depends on the specific variety and processing techniques used (Suma and Urooj, 2012) [20]. These bioactive substances enhance its capacity to scavenge free radicals, by DPPH (1,1 diphenyl 2 picrylhydrazyl) radi cal inhibition (IC50 values ranging from 1.2 to 2.8 mg/mL) and ABTS (2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid)) radical scavenging performance (IC50 values between 0.9 and 2.1 mg / mL). The presence of phenolic acids increases its antioxidant capacity, rendering i t capable of neutralizing reactive oxygen species (ROS). Moreover, its flavonoids, such as apigenin and luteolin, regu late antioxidant enzymes including such as superoxide dismutase (SOD) and glutathione peroxidase (GPx) enhancing cellular protection.

Germination greatly boosts the antioxidant activity of foxtail millet by raising the levels of phenolic and flavonoid compounds. (Sharma *et al.,* 2015) [19] found a significant increase in antioxidant activity after germination, with peak free-radical scavenging activity around 90.5% under optimized conditions.

This enhancement was significantly linked to a rise in the total phenolic and flavonoid levels, suggesting that germination enhances the release and formation of bioactive compounds that contribute to the antioxidant capacity. The research emphasizes germination as a beneficial process ing technique to enhance functional and health boosting attri butes of foxtail millet.

b. Antidiabetic and glycemic control

Foxtail millet has shown considerable promise in controlling diabetes and enhancing glycemic regulation because of its gradual carbohydrate breakdown.

The grain contains a high level of dietary fiber (6.7-8.0%) and resistant starch (1.2-2.5%), leading to a low glycemic index (GI 50-58), which facilitates slow glucose release and averts spikes in blood sugar after meals (Sahoo *et al.,* 2025).

Bangoura *et al*. (2012) also found that insoluble dietary fibers from foxtail millet can slow down how glucose moves through the digestive system and help the body absorb it better. These fibers can also stop the enzyme alpha-amylase from breaking down carbohydrates quickly, which helps reduce the amount of glucose that enters the bloodstream. Many other studies have shown that the various active chemicals in the seed coat of foxtail millet, such as phenolic compounds, carotenoids, and tocopherols, have important health benefits. These chemicals act as antioxidants, cancer fighters, inflammation reducers, blood pressure controllers, and help manage blood sugar levels. They are useful in preventing serious health issues like cancer, heart diseases, diabetes and high blood pressure. Research indicated that diets containing foxtail millet led to significant decrease in

fasting blood glucose levels (Goel *et al.,* 2025). Furthermore, its flavonoids and polyphenols (eg., quercetin and ferulic acid) suppress carbohydrate digesting enzymes such as α-amylase and α-glucosidase (Candra *et al.,* 2025) [5]. Foxtail millet improves insulin sensitivity thanks to its bioactive components, including magnesium (~130 mg/100 g) and phytochemicals such as vitexin and orientin (Gowda *et al.,* 2022) [8]. Studies have indicated that consuming foxtal millet enhances insulin sensitivity in type 2 diabetes patients , linked to its antioxidant and anti-inflammatory effects.

c. Cardioprotective benefits

Foxtail millet has shown considerable heart-protective properties. impacts, mainly by decreasing low-density lipoprotein (LDL) cholesterol and fostering overall cardiovascular well-being (Gowda *et al.,* 2022) [8]. A research investigation revealed that the soluble diatery fibre and polyphenols in foxtail millet significantly reduce LDL cholesterol levels by blocking cholesterol uptake in the intestine and improving its elimination (Candra *et al.,* 2025) [5]. Moreover, the grains elevated fiber levels help enhance lipid metabolism, lowering the likelihood of atherosclerosis and coronary arterial disease. The existence of vital fatty acids, like linoleic acid, additionally aids in its ability to lower cholesterol, enabling foxtail millet an important nutritional element for heart health illness prevention (Zhang *et al.,* 2017) [22]. Magnesium functions acting as a natural calcium channel inhibitor, facilitating vasodilation and lowering vascular resistance, which aids sustaining normal blood pressure ranges (Sharma *et al.,* 2015) [19]. Fiber content further contributes to controlling hypertension by enhancing endothelial performance and lowering oxidative pressure. Research emphasizes that consistent intake of foxtail millet greatly lowers the systolic and diastolic blood pressure.

d. Gut health and probiotic potential

Foxtail millet has been demonstrated to serve as an effective substrate and carrier for probiotic functionality, aiding both the viability of probiotics in food systems and the beneficial microbial activity within the gut. In formulated probiotic powders, the naturally high protein and dietary fiber content of foxtail millet contributed to the protection of probiotic microorganisms during processing and storage, ensuring sufficient viable counts and showcasing its appropriateness as a stable probiotic carrier (Santosh *et al.,* 2025). In the context of fermented beverage formulations, foxtail millet facilitated active probiotic fermentation, and when paired with additional prebiotics, it further promoted probiotic growth, metabolic activity, and microbial stability throughout storage without compromising sensory quality, thereby indicating a synergistic synbiotic effect (Fathima *et al.,* 2021). Overall, these findings suggest that foxtail millet acts both as a protective food matrix for probiotics and as a prebiotic-rich ingredient that enhances probiotic survival, activity, and gut microbial functionality, underscoring its significant potential for application in probiotic and synbiotic food products.

Effects of processing on nutritional property of foxtail millet

1. **Protein:** Some harmful substances in foxtail millet, like phytates and trypsin inhibitors, can make it harder for the body to digest its proteins. Different processing methods such as dehulling, milling, soaking, heating, germination, fermentation, and popping help reduce these harmful substances and make the protein easier to digest in the lab. Studies show that cooking with an alkaline solution, fermentation, germination (for 40 hours at 25°C), and popping greatly improve the quality of protein in foxtail millet. Heat treatments also help by breaking down the connection between protein and starch, and by turning off the harmful substances. Germination and fermentation are especially helpful because they increase protein levels by making more amino acids and improve digestibility by breaking down phytates with enzymes and changing hard-to-digest proteins into ones that are easier to use. But if you remove too much of the outer layer, you might lose some protein (Gowda *et al.,* 2022) [8].

2. **Carbohydrate:** The amount of carbohydrates in foxtail millet goes up by 1.29%. However, in pearl millet flour, the carbohydrate levels don't change much in the first 24 and 48 hours of germination, but they drop a lot after 72 hours. The rise in carbohydrates during the germination of foxtail millet is linked to lower levels of moisture, ash, protein, and fat, as these factors are connected to how much carbohydrate is in the grain. (Gowda *et al.,* 2022) [8].

3. **Dietary fibre:** A study on the impact of milling on the fiber components of foxtail millet revealed that the insoluble dietary fiber content of lignin, cellulose, and hemicellulose in the milled part had less content compared to the whole millet flour, but in foxtail millets, the fiber amount went up a lot as the germination time increased. This is perhaps due to a change in the structure of the seeds' cell wall polysaccharides, which may affect the tissue histology and disrupt protein carbohydrate interaction.

4. **Mineral**: Germination greatly enhances the bioavailability of mineral in foxtail millet by changing its nutrient composition and decreasing antinutritional components like saponins, polyphenols, and phytates that restrict mineral uptake. Phytase enzymes are activated during germination, which releases bound minerals. Consequently, high concentrations of essential minerals, such as magnesium, sodium, calcium, and iron, have been observed in sprouted foxtail millet (Sharma *et al.,* 2015) [19]. Milling research reveals that whole-grain foxtail millet flour maintains higher mineral levels, while polished flour has lower minerals but higher protein content. (Gowda *et al.,* 2022) [8]. Moreover, solid-state fermentation boosts mineral and amino acid levels, especially when foxtail millet flour is fermented with *Lactobacillus acidophilus*, demonstrating the efficacy of biological processing techniques in enhancing mineral accessibility.

5. **Fat:** The time it takes for germination affects lipid levels. For example, the unprocessed and refined flour from sprouted foxtail millet contained 4.4% and 3.6% fat, which was significantly lower lower than that of non-germinated sample. This happens because the fat serves as a source of energy during the germination

process that results in a decrease following germination (Sharma *et al.*, 2015) [19]. A research project aimed at examining the impact of high pressure soaking on the nutritional properties of foxtail millet showed that the fat level decreases by 27.98% (Gowda *et al.*, 2022) [8]. This was due to the enzymatic process that soluble and available nutrients during the germination stage in foxtail millets. Germination of foxtail millet was observed to lower the fat content, which is linked to lipid breakdown and fatty acid oxidation that takes place during germination. The grains of foxtail millet were germinated at 30°C, while little millet was germinated at 35°C for a duration of 24 hours following soaked overnight, followed by tray drying at 60°C for 6 hours and then milled for additional analysis. The fat content decreased by 17.84% in foxtail millet and rose by 25.95% in little millet (Reddy *et al.*, 2021) [17]. This occurred because of the alterations in energy values as the fat content comprises roughly double the energy amounts of protein and carbohydrate.

Utilization of foxtail millet in food

Modern day use of foxtail millet (*S. italica*) in food systems shows that these small grains are packed with nutrients like carbohydrates, protein, antioxidants, and other important elements. Even though they offer many health benefits, they are also very good at growing in tough weather conditions. Millets have good qualities that make them work well with different ways of processing.

To prepare millet for different food uses, people usually do a series of steps. The first steps include wetting, removing the husk, and grinding. Then there are other steps like grinding more, fermenting, extruding, malting, making gelatin, popping, and roasting. These steps help turn millet into many different kinds of foods with different textures and tastes (Amadoubr & Le, 2013) [2]. The physical and chemical features of starch determine how it works in different areas. Foxtail millet starch is mostly made up of amylose, which can be used to make resistant starch products like thickening agents, binders, flavor protectors, emulsion stabilizers, gelling agents, and more (Dimri & Singh, 2022) [6]. Since it is gluten-free, it is a good option for people with celiac disease.

However, because foxtail millet is small in size, there are not many ways to process and use it effectively in ready-to-cook or ready-to-eat foods. Creating new and better processing methods, such as extrusion, high pressure treatment, and enzyme breakdown, could help increase the use of foxtail millet in food.

Conclusion

Foxtail millet is a nutritionally rich and functionally versatile cereal with significant antioxidant and health promoting properties. Its unique combination of dietary fiber, essential minerals and bioactive compounds contribute its role in reducing the risk of diabetes, cardiovascular diseases, gastrointestinal disorders and certain cancers. Promoting foxtail millet through dietary diversification, processing innovation and public awareness can contribute meaningfully to sustainable nutrition and public health.

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