Biointerface Research in Applied Chemistry
Open-Access Journal (ISSN: 2069-5837)

Review
Volume 13, Issue 4, 2023, 338
https://doi.org/10.33263/BRIAC134.338

Bioactive Components and Health Benefits of Maize-based Fermented Foods: A Review

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Scopus Author ID 51864139900

Received: 3.05.2022; Accepted: 9.06.2022; Published: 11.09.2022

Abstract: Maize is one of the very important cereals which contains major nutrients, carbohydrates, proteins, vitamins, minerals, and various other constituents like β-glucan, oligosaccharides, and resistant starch. Maize contains various bioactive components like phenolic acids, flavonoids, carotenoids, and phytosterols. These effectively prevent and cure diseases such as night blindness, age-related disorders, cardiovascular and neural disorders, and colon cancer. The fermentation of maize using Lactic Acid Bacteria to produce traditionally fermented foods is one of the ancient health-promoting formulae to achieve the health benefits of cereal ingredients and live beneficial bacteria. These microbes exert various probiotic effects on consumer health and are explored as a source of probiotic strains. The fermented maize-based foods are economical, have enhanced sensory and nutritional quality, reduce the risk of detrimental diseases, improve shelf life, and produce antimicrobial substances and health-stimulating compounds. This review emphasizes maize's nutritional and phytochemicals composition, diversity of important maize-based fermented foods and beverages, health benefits of consumption, and future perspectives and challenges.

Keywords: maize; fermented food; beverages; mycotoxin; bioactive components; phytochemicals; phytates.

1. Introduction

Maize or corn (*Zea may L.*) is an important cereal crop that belongs to the Poaceae family. Maize has wider adaptability and the highest genetic yield potential among cereals. It is a tall annual herbaceous grass sized 2-20 feet in height and growing in tropical and temperate regions. The genera Zea consists of five species *Zea deploperennis, Zea luxurians, Z. nicaraguensis, Z. perennis*, and *Z. mays. Z. mays* is the only species cultivated for human and animal use, while the remaining four are wild grasses. The maize plant is classified in Plantae-

Kingdom, Poaceae- family, Zea- genus, mays- species. It has many synonymous like maize, mealie, corn, etc. Maize can be cultivated in various soils, climates, and biodiversity. However, soils with sufficient organic matter, high moisture retention capacity, and neutral pH are preferred for higher yield. Maize is a large grain plant that originated from Mesoamerica, the Mexican highlands from where it spread and domesticated at least 6,000 years ago by indigenous people of Mexico [1].

Nevertheless, there is no evidence that maize was a staple grain then [1]. It spread to other parts of the world after the discovery of America by Europeans in the 15th century. Regardless of origin, it has become an adaptable crop for diverse agro-climatic zones. The word "Maize" is derived from "mahiz", a Spanish word for the plant, and several maize types can be discerned based on endosperm, color, and kernel composition. The major types of maize are sweet corn, pod corn, flour corn, dent maize, floury maize, flint maize, blue corn, waxy maize, Pignoletto, Japanese stripped maize, otto file, Nostrano Dell'Isola.

Presently, maize is cultivated in 197 million ha of land in more than 170 countries, and the estimated production is about 1147.7 million metric tons (MT). It is 39% of total cereal production and 27% of total cereal cultivated area globally[2]. The major contributor was the United States producing 383.94 MT maize, whereas the other significant players are Brazil, China, Mexico, Argentina, India, France, Indonesia, Australia, South Africa, and Italy. Global maize cultivation is estimated to increase to 241 M ha in 2030 and is expected to become the most widely cultivated crop worldwide in the coming decade. The estimated 216 M maize farms globally in 2020 is estimated to increase by 5% to 227 M by 2030. China and India remain the countries with the most maize and wheat farms [3]. The major portion of maize production is used as animal feed and as human food, and the remaining as industrial raw ingredients.

Most cancer deaths are due to diets, so future research and innovation focus on modifications of diets to prevent diseases [4]. Maize constituents have good antioxidant activity, but most phenolic acids occur in bound form as a conjugate with sugars, fatty acids, or proteins. Chemical and enzymatic hydrolysis techniques are generally used to achieve the maximum yield of phenolic acids. However, the chemical method is reported to reduce the phenolic content, and the enzymatic method is not considered economical. Therefore, the fermentation of maize is a good alternative to modifying phenolic content and antioxidant potential [5].

Fermentation of foods is one of the ancient [6]and cheapest [7] food processing techniques to extend the shelf life of food [8] and improve nutritional and sensory characteristics [9]. A major part of cereal, including maize, is traditionally fermented to obtain various beverages, porridges, dough, and gruels. These items are widely consumed, contributing substantially to the safety and diversity of human diets, notably in Africa and Asia. The cereal-based fermented products are nutritionally superior to their native counterparts [10]. The fermented foods and beverages traditionally used maize are ogi, uji, boza, akamu, pozol, Raabadi (“Makki ki Raab”), mahewu, cheka, and liha are a few of them.

This paper reviews the bioactive components of maize, the diversity of maize-based spontaneously lactic fermented foods of Africa and Asia and associated microflora, their potential health benefits of consumption, nutritional changes that occurred during fermentation, and future perspectives. There is a need of the hour to ensure both food and nutrition security and a thorough understanding of maize-based fermented food and beverages to feed the current and future population.

2. Nutritional Composition of Maize

Maize kernel is an edible and nutritive part of the plant [11]. It is a good energy source due to carbohydrate content and is treated as an important cereal grain in many countries of Africa, Asia, and the American pacific [12]. It is deficient in essential amino acids, lysine, and tryptophan. The whole grain flour of maize contains carbohydrates (76.85%), dietary fiber (7.3%), total protein (6.93%), total solids (3.86%), and ash (1.45%), whereas β-glucan content found in the range of 0.8 to 1.7% [20]. The edible part contains vitamin B_1 (thiamine), vitamin C, vitamin E, vitamin K, niacin, riboflavin, pantothenic acid, vitamin B_6, and folic acid [11]. It also contains dietary fiber, amino acids, and minerals. The maize kernel contains the important mineral potassium, which is also not found in sufficient amounts in other regular diets of human beings. Maize germ oil contains linoleic acid 58-60%, oleic acid 24-26%, palmitic acid 9-10%, stearic acid 1.7-1.8%, and linolenic acid 0.7-1.1% [13]. Maize germ oil was obtained using a wet milling process from the germ. The vitamin E in our daily intake is found in two major types alpha (α) and gamma (γ) tocopherol. Corn germ oil is considered a very good source of these two forms of tocopherols. The germ oil contains 21.3 mg/100 ml α-tocopherol and 94 mg/100 gm γ-tocopherol. There are two more by-products of wet milling used as animal feed: corn gluten feed (protein content more than 20%) and corn gluten meal (low fiber content and around 60% protein). Maize silk contain carbohydrates (65.5-74.3%), protein (9.42-17.6%),moisture (9.65-10.4%), dietary fiber (7.34%), fat (0.29-4.74%), and ash (1.2 -3.91%) [14]. It contains various other constituents necessary for our daily food intakes, such as minerals (Sodium, calcium, zinc, iron, potassium, manganese, magnesium, and copper) maizenic acid, fixed oils, and resign, mucilage, and fiber [14].

3. Bioactive Ingredients of Maize

The non-nutritive bioactive ingredients naturally found in different parts of plants are known as phytochemicals. These ingredients are beneficial to human health due to their antioxidant activity, microbial inhibitory activity, and other biological attributes. It also has the potential to reduce the hazard of various chronic diseases [15] and is important for the development of pharmaceutical products. The different part of the plant, such as seed, silk, stem, leaves, and roots, contains phytochemicals but are mainly distributed in the kernel and bran. The various phytochemicals found in maize are flavonoids, phenolic acids, steroids, carotenoids, alkaloids, saponins, tannins, anthocyanins, and other phenolics [15,16]. The content of phenolic compounds varies among different maize varieties, and high carotenoid corn has the highest phenolic content, followed by yellow corn, blue corn, white corn, and red corn [17].

3.1. Phenolic.

3.1.1. Phenolic acids.

Phenolic acids are one of the abundantly found phytochemicals of maize [18] and are reported to be effective in treating cancer [19]. Further, these compounds can be subdivided into hydroxybenzoic acid and hydroxycinnamic acid derivatives [15]. The sour, bitter, and astringent taste in maize is mainly due to phenolic acids in the range of 40-90 ppm [17]. The major phenolic acids detected in maize are ferulic acids found predominantly in the bound form.

3.1.2. Flavonoids.

Flavonoids are secondary metabolites synthesized mainly by plants [20], and these are the phenolics found in the highest amount in maize. The risk of chronic diseases, cancer, and diabetic disorders can be mitigated by higher consumption of flavonoids [21]. These bioactive ingredients provide plant protection against microorganisms and insects and safety for animals against various diseases [22]. Flavonoid content varies among maize varieties; the most widely used maize contains about 1.68 ±0.17 µ mol catechin equiv/g. There are various categories of flavonoids, i.e., flavanols, anthocyanins, isoflavonoids, and flavones. Anthocyanin is a major category of flavonoids responsible for the purple to the pinkish color of the corn, depending on the pH levels. Anthocyanins were reported to show a positive effect on health, i.e., reduced risk of cancer and anti-inflammation effect [23]. Anthocyanins are phenolic compounds with bioactivity that bring health benefits such as anticarcinogenic [24], antioxidant [25], anti-inflammatory, antihemorrhagic, and improved visual acuity [26].

3.2. Carotenoids.

Carotenoids are responsible for various coloring pigments, i.e., yellow, orange, and red. Carotenoids are beneficial because it is a precursor of vitamin A and act as antioxidants [27]. Vitamin-A deficiency in the human being can cause night blindness, enhanced mortality and delayed growth in children, dry skin, and infertility in people of developing countries [28]. The various processing factors, like homogenization and heat treatments, may enhance carotenoid bioavailability [29]. The carotenoids have various important roles apart from acting as vitamin A precursors, such as important pigment photosynthetic reactions, protecting from photooxidation, and attracting pollination-causing insects. The carotenoid content in maize is classified into two groups, (i) carotenes (α-carotene and β-carotene, which have carbon and hydrogen (ii) xanthophylls (β-cryptoxanthin, zeaxanthin, and lutein, which have only oxygen group). The highest provitamin A activity reported in the β-carotene isoform is transformed easily in vitamin A during human metabolic activity [28].

3.3. Vitamin E.

The vitamin E content in maize is relatively abundant, and the γ-tocopherol isomer is the largest part of the whole vitamin E. Vitamin E protects from various diseases such as Alzheimer's, cardiovascular and nerve system-related disorders, and old age degeneration [30].

3.4. Phytosterols.

Corn is also a good source of phytosterols. Steryl ester is a major part of total phytosterol content, 55-60%. This esterified form of sterol is much lower in other vegetable oils. The researcher found more than 250 phytosterols so far, categorized into 4 groups: 4-demethylsterols or simple sterols, 4, 4-dimethyl sterols, 4-monoethyl esters, and sitosterols. The categorization is based on the number of methyl groups at the C-4 position. The most predominant phytosterols extracted from oil are sitoslevo (approximately 77-87%), campesterol (13-23%), stigmasterol, and delta-5 avenasterol [17]. The concentration of phytosterols varies in different fractions of corn kernel, such as endosperm, germ, and pericarp, but the highest phytosterol was found in the endosperm fraction. The consumption of plant phytosterols was reported to lower the total cholesterol level, including serum LDL [31]. The concentration of important antioxidant micronutrients and phytochemicals are shown in table 1.

Table 1. Phytochemical composition of maize.

Antioxidant micronutrients						**Ref.**
Tocopherol and tocotrienol (mg/100 g grain)	Folate (µg/10g grain)	Zinc (mg/100g grain)	Iron (mg/100g grain)	Copper (µg/100g grain)	Selenium (µg/100g grain)	[32]
6.6	110–170	1.7	1.5	240	12.0	
Phytochemicals compounds						
Polyphenols(mg gallic acid eq/100g grain)	Ferulic acid (mg/100g grain)	Betaine (µg/g Dry Weight)	Phyticacid (mg/100g grain)	Carotenoids (µg/100g grain)	Alkylresorcinols (mg/100g grain)	[17, 32, 33]
39–711	177	107-304	940	969–1300	-	

-Not Available

4. Diversity of Traditionally Maize-based Fermented Foods and Beverages and Associated Microflora

The Lactic Acid bacteria are widely and predominantly used for the fermentation of corn either in a single culture or mixed culture [12,34]. The commonly found LAB species in these products belong to genera of *Lactobacillus, Streptococcus, Leuconosto*c, *Pediococcus*, and *Micrococcus*, although *Lactobacillus* species are the predominant microbes [12,35]. In certain products, fungi are also reported to play an important role in fermentation other than bacteria such as *Saccharomyces, Cladosporium, Aspergillus, Trichothecium, Paecilomyces, Fusarium*, and *Penicillium* [36]. Apart from major nutrients (carbohydrates, proteins, vitamins, and minerals), maize has several constituents like water-soluble fiber (e.g., β-glucan), oligosaccharides, and resistant starch, which help to promote the growth of beneficial bacteria.

Table 2. The genus of LAB associated with maize-based fermented foods.

Genus of LAB	**Oxygen Requirement**	**Cell Characteristics**	**Gram Reaction**	**Catalase Test**	**References**
Lactobacillus	Facultative anaerobe	Rod-shaped (Bacilli; Cocobacilli)	Positive	Negative	Adopted and modified from [37]
Lactococcus	Facultative anaerobe	Coccus shaped	Positive	Negative	
Streptococcus	Facultative anaerobe	Coccus shaped	Positive	Negative	
Pediococcus	Facultative anaerobe	Coccus spheres in tetrads	Positive	Negative	
Leuconostoc	Facultative anaerobe	Coccus spheres in the chain	Positive	Negative	
Propiniobacterium	Facultative anaerobe	Rod-shaped	Positive	Negative	
Bifidobacterium	Facultative anaerobe	Rods in branched shape	Positive	Negative	
SporoLactobacillus	Facultative anaerobe	Rod-shaped	Positive	Negative	
Carnobacterium	Facultative anaerobe	Coccus shaped	Positive	Negative	
Lactosphaera	Facultative anaerobe	Coccus shaped	Positive	Negative	
Oenococcus	Facultative anaerobe	Coccus shaped	Positive	Negative	
Fructobacillus	Facultative anaerobe	Rod-shaped	Positive	Negative	
Vagocuccus	Facultative anaerobe	Coccus shaped	Positive	Negative	
Weisella	Facultative anaerobe	Coccus shaped	Positive	Negative	
Aerococcus	Facultative anaerobe	Coccus shaped	Positive	Negative	

These compounds stimulate the growth of probiotic microbes like *Lactobacillus* and *Bifidobacterium* found in the gastrointestinal tract, thereby being considered a prebiotic. The presence of various phytochemicals and other bioactive ingredients in maize makes it one of the suitable carriers for probiotics to develop functional foods.

Lactic acid fermentation is important for maize processing to produce fermented beverages and foods with extended shelf life, decreased antinutrients, improved nutritional value, texture, and sensory attributes, and health benefits of ingestion of live LAB [37]. In such fermentation, initially, LAB is dominated by microflora which produces amylases for the utilization of sugar and, subsequently the production of energy [38]. Based on carbohydrate (sugar) utilization patterns, LAB is classified into two categories, i.e., homofermentative and heterofermentative. The end metabolic product of homofermentative microbes (*Streptococcus, Pediococcus, Lactococcus*, and some spp. of *Lactobacilli*) are lactic acid, whereas heterofermentative (*Leuconostoc, Weisella*, and some spp. of *Lactobacilli*) produces ethanol, and CO_2 apart from of lactic acid. LAB also produces other products like H_2O_2, bacteriocins, flavoring compounds, and short-chain fatty acids, which exert an antimicrobial effect on other spoilage-causing microbes. Table 2 summarizes the various LAB genus found in cereal-based fermented products.

These microbes are also reported to decrease tannin content in many high tanning content crops to improve iron absorption [39]. Cereals, including maize, are good methionine and cysteine sources but lack lysine. Cereal-based foods are fortified with legumes rich in lysine to overcome this limitation. Further, foods fermented by LAB also have been reported to produce compounds responsible for antiviral [40,41] and antitumor activities [38]. Due to various beneficial properties, some LAB is considered probiotics. In addition to the health benefits, the development of fermented foods has various other advantages like reduced loss of raw material, reduced cooking time, and decreased fuel requirement. The various most important spontaneously maize-based fermented foods and beverages are summarized in table 3.

Table 3. Traditionally fermented maize-based fermented foods and beverages.

Name of Fermented Product	**Microbes associated**	**Country**	**Description**	**References**
Akamu	LAB (*Lactobacillus* spp.), Yeasts (*Candida, Clavispora, Rhodotorula, Saccharomyces* spp.), and other non-LAB (*Bacillus* and *Pseudomonas* spp)	West Africa	Porridge	[42]
Boza	*Weissella confusa, Enterococcus, Lactococcus, Bacillus,* and *Lactobacillus spp.*	North Africa	Beverage	[10,35,43]
Maize based Cheka	Unknown	SouthWestern Ethiopia	Beverage	[44]
Chicha	LAB (*Lactobacillus, Lactococcus, Enterococcus, Leuconostoc, Weisallae*) and yeasts (*Candida, Hanseniaspora, Kluyveromyces, Pichia, Torulaspora, Rhodotorula*)	Peru, Ecuador	Alcoholic Beverage	[45–47]
Koko	*L. plantarum, L. brevis,* and *Saccharomyces cerevisiae*	Ghana	Porridge	[12]
Kenkey	LAB (*L. fermentum, L. reuteri*) and yeast (*Candida spp., Saccharomyces cerevisiae)*	Ghana	Dough	[12]
Kunu	Species of genus *Lactobacillus, Lactococcus, Leuconostoc,*	West Africa	Beverage	[48]

Name of Fermented Product	**Microbes associated**	**Country**	**Description**	**References**
	Pediococcus, Weissella, Acetobacter, Propionibacterium, Gluconacetobacter, and *Gluconobacter*			
Liha	Unknown	Ghana, Togo, Benin, Nigeria	Beverage	[12]
Lohpani/Bhangchang	*Not reported*	India	Beverage	[49]
Makai ko jaanr	*Not reported*	India	Beverage	[49]
Mahewu/Amahewu	*L. delbrueckii, L. bulgaricus, Streptococcus lactis, Leuconostoc spp.*	S. Africa, Zimbabwe, Togo	Beverage	[50]
Mawe	*Lactobacillus fermentum, Pediococcus acidilactici Weissella confuse, Pichia kudriavzevii, Kluyveromyces marxianus,* and *Saccharomyces cerevisiae*	West Africa, Nigeria	Dough	[37,51]
Munkoyo	*Predominant families Streptococcaceae, Leuconostocaceae, Enterobacteriaceae, Lactabacillales, Bacillaceae and Aeromonadaceae*	Zambia, Katanga, Congo	Beverage	[52,53]
Mutwiwa	LAB including *Pediococcus pentosaceus*	Zimbabwe	Porridge	[10,54]
Obiolo	Not reported	Nigeria	Beverage	[55]
Ogi, Ogi-Baba	LAB (*Lactobacillus, Lactococcus, PediococcusWeissella* spp), Yeast (*Klebsiella, Aspergillus, Fusarium, Mucor, Penicillium,Rhizopus*) and *Bacillus*sp.	Nigeria, W. Africa	Pudding	[56,57]
Pito/dolo	*Lactobacillus spp., LimosiLactobacillus spp., Pediococcus spp., Leuconostoc spp., Streptococcus spp.,* and *Saccharomyces cerevisiae*	West Africa	Beverage	[58]
Pozol	*Weisella spp., Streptococcus bovis, Streptococcus infantarius, Streptococcus macedonicus, Lactobacills spp., Enterococcus spp.*	Mexico, Guatemala	Beverage	[59,60]
Puda/Pudla	Lactic acid bacteria, yeasts	India	Snack	[49,61]
Raabadi (Maize porridge)	*Lactobacillus plantarum, Pediococcus acidilactici, Bacillus* sp., *Micrococcus* sp., yeasts	India	Mild-acidic, thick slurry-like product	[49,62–64]
Tarhana (Maize)	*Lactobacillus* spp, *S. cerevisiae* *Bacillus* spp, *Enterococcus* spp., and *Streptococcus* spp	Greece, Cyprus, Turkey	Soup	[65]
Tella	*Saccharomyces cerevisiae*	Ethiopia, Egypt	Beverage	[55]
Tobwa	Lactic Acid Bacteria	Zimbabwe	Beverage	[10,12]
Togwa	Yeast (*Candida, Kluyveromyces, Pichia, Saccharomyces* spp), LAB (*Lb. brevis, Lb. fermentum, Lb. plantarum, W. confuse*)	Tanzania	Beverage	[12,37]

Name of Fermented Product	Microbes associated	Country	Description	References
Uji	*Lactobacillus plantarum*	Uganda, Kenya, Tanzania	Beverage	[10]

4.1. Ogi.

Ogi, fermented cereal porridge prepared using cereals (maize/sorghum) commonly used as weaning food formulae for newborns in West African countries [11]. However, adults and old people also consume it as a breakfast meal. Ogi is traditionally produced with 40 days estimated shelf life, but semi-industrial production is also reported using a starter culture. *Lactobacillus plantarum* is the prominent microbe for lactic acid production, and starch hydrolysis is done by *Coryne bacterium*, whereas flavor production is associated with *Saccharomyces cerevisiae* and *Candida mycoderma* in ogi [12].

4.2. Mahewu.

Mahewu is a fermented maize meal widely prepared and used in South African countries and some parts of the Gulf countries. It is prepared by mixing maize in boiling water (1: 9 ratio), cooking (10-15 min), cooling (room temperature), and then being allowed to ferment by indigenous microflora after keeping it in a container. It is prepared at the household level (shelf life up to 25 days) and in some industries of South Africa in the form of liquid or powder (precooked instant ready mix). The predominant microflora in traditionally prepared mahewu is *Lactococcus lactis* subsp. *lactis*, however, use of commercial starter culture (*Lactobacillus delbruckii* ssp. and/ or *Lb. bulgaricus*) was also reported [12].

4.3. Uji.

Uji is a spontaneously fermented beverage prepared by blending maize/millets, flavors (cassava) in hot water, then fermentation (24-72 h) at room temperature or close to flames, the addition of water for dilution, followed by boiling and sweetening. *Lactobacillus plantarum*is major microflora associated; however, other LAB species like *Pediococcus acidi lactici*, *Lb. fermentum*, *Lb. paracasei*, and *Lb. buchneri* is also involved in fermentation [12,13].

4.4. Raabadi.

Raabadi is a popular, traditionally fermented cereal-based beverage consumed daily in North-Western India [14,15]. It is a very important staple food and provides nutrition and energy to millions of people having low and average incomes in India. It is prepared by mixing and fermenting the cereal flours (wheat, barley, maize, pearl millet, or sorghum) with chhaschh or buttermilk, followed by boiling with continuous stirring for 15-20 minutes and addition of salt as per need. Then the prepared product is cooled and served directly or after blending with buttermilk as a breakfast beverage.

5. Beneficial Aspects of Consumption of Maize-Based Fermented Foods

5.1. Extend shelf-life, food safety, and preservation.

Traditional fermented products with enhanced nutritional and traditional attributes (fig.1) often produce metabolic compounds inhibiting pathogenic and spoilage-causing microbes [10]. The produced metabolites, such as organic acids (Lactic acids, propionic acid, acetic acid, etc.), ethanol, hydrogen peroxide, peptides, fatty acids, etc., causes inhibitory action for numerous microbes [66]. The organic acids decrease the pH of the food matrix, causing acidic environments, which are microbial growth control factors for most microbes, especially bacteria. Ethanol, H_2O_2, and other secondary metabolites can act as antibacterial and antifungal agents. Some LAB and yeast's antifungal and antimycotoxin-producing abilities are of great significance for cereal-based products, as mycotoxin production can cause public health hazards [67]. Heat preservations of food have been used for a long time, but intense heat exposure can negatively impact food's sensory and nutritional quality[68]. To avoid these limitations, the food processors started using additives such as chemical preservatives with reduced thermal treatments, compensating for the quality losses to some extent. Biopreservation approaches use natural compounds originating from microbes (bacteria and yeasts), plants, or animals to increase the shelf life of food while preserving its safety [68]. These substances may be primary and/or secondary metabolites, which attracted the interest of food manufacturing companies due to their ability to avoid lipid oxidation, color degradation, and extension of shelf life with improved food safety. The most widely used biopreservation approach is to use antimicrobial substances to prevent spoilage-causing microbes and food-borne pathogens. These substances should not exert any adverse effect on the gastrointestinal microbiota of the host but should destroy targeted undesirable spoilage microbes or pathogens [68]. These bio-molecules, with other barriers, are also used to prevent food spoilage, known as the hurdle technology approach. Schettino *et al*. (2020) used the *Lactoplatibacillus plantarum* LB1 and *FurfuriLactobacillus rossiae* LB5 to extend the shelf life of pasta [8]. This study used Penicillium roqueforti as a fungal contaminant in fresh pasta products and tested with or without adding calcium propionate as a reference.

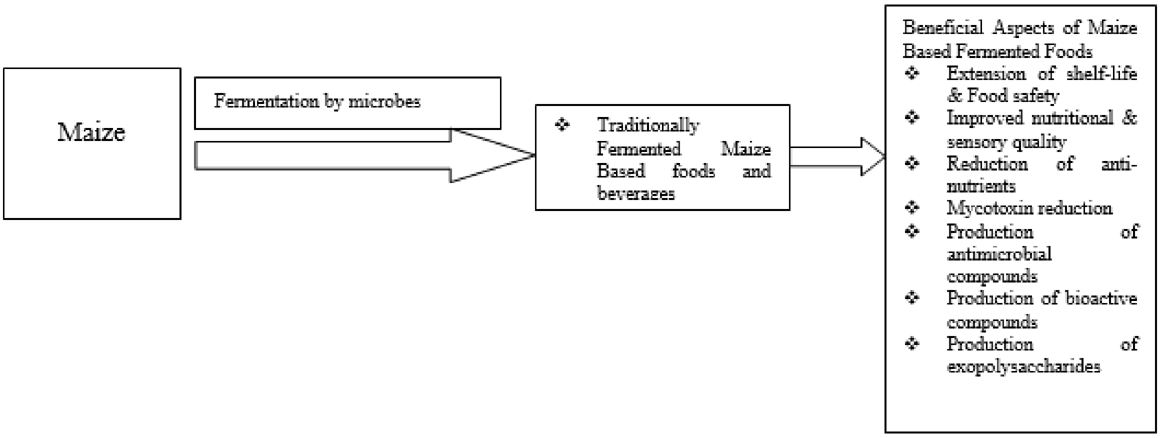

Figure 1. Health implication of maize-based fermented foods and beverages.

5.2. Improvement in the nutritional composition of fermented foods.

5.2.1. Improved protein and carbohydrate digestion.

Fermentation by lactic acid bacteria improves protein digestibility [69]. The proteolysis of a protein depends on its structure, antinutrient compounds (Protease enzyme inhibitor, phytases), and physiological attributes such as temperature, the strength of ionic bonds, and pH. Protein is degraded in the small intestine by enterocytes in amino acids and peptides; however, if it enters the large intestine, the proteins are degraded in amines and short-chain fatty acids by the microbiota of the guts. These fermentation metabolites induce various reactions and mechanisms which lead to neurotransmission and immunomodulation [10]. Cereals, including maize, often have fewer amino acids, especially lysine. Lactic fermentation is commonly employed to improve the nutritional profiles of maize-based products. Fermentation of maize flour by *Lactobacillus plantarum, Saccharomyces cerevisiae*, and their co-culture combination was reported to increase protein content (more than 35%) and protein digestibility (more than 30%). *Lactobacillus plantarum* strain fermented maize flour showed the maximum increase in protein content and digestibility compared to others [70].

Digestion of carbohydrates is a very important aspect of human health and the functioning of the body. Starch fermentation by LAB produces lactic acid, which facilitates interactions between starch and gluten content. This reaction mechanism lowers the availability of starch and the Glycemic Index of the food [71]. A very limited LAB species have the gene amyA responsible for the amylolytic activity. The gene amyA produces lactic acid from starch. The most active amylolytic LAB genes are lactobacilli (e.g., *Lactobacillus amylovorus*), and genus *Lactobacillus*, *Lactococcus*, and *Streptococcus* show the highest starch digestion activity [12]. The easily fermentable sugars "Fermentable oligo-, Di- and Monosaccharides and polyols" (FODMAP), e.g., fructose, lactose, galactans, are not generally recommended for the patient having irritable bowel syndrome (IBS). These sugars reach the large intestine and are fermented by gut microbiota; as such, types of sugars are not absorbed by the small intestine. Due to this fermentation, abdominal abnormalities like diarrhea, constipation, pain, swollen belly, etc., were observed. Even after full or partial degradation of these sugars, its reduction has some health benefits also, since its adverse effect depends on the intake dose of these sugars. There are very limited reports about the preparation of cereal foods with lower content of fermentable digestible sugars. Struyf*et al*. (2017) produced an experimental whole wheat bread in which 90% of these sugars were reduced by using the starter culture *Kluyveromyces marxianus* and *Saccharomyces cerevisiae* (baker's yeast)[72]. Moro *et al*. (2018) demonstrated that the use of LAB and yeasts in combination to prepare value-added bread suitable for specific dietary requirements is a good approach without affecting any quality attributes[73].

5.2.2. Improved dietary fiber.

Dietary fibers are plant sugars that are not easily hydrolyzed by enzymes of human origin but fermentable by microbes in the large intestine [10]. These Dfs have an important role in human health and physico-technological attributes of foods. These are classified on the basis of solubility criteria: soluble and insoluble dietary fiber. Cereal dietary fibers are "sugars other than starch, i.e., "arabinoxylans, B-glucans, cellulose, resistant starch, fructans, and lignin," which generally have complex structures with other smaller molecules, e.g., phenolics, minerals [74]. Fermentation of cereals decreases food pH, stimulating different endogenous enzymes and/or microbial enzymes. These enzymes degrade biopolymers, which leads to softening of cereal grains and enhancing the cereal-based fermented product's sensory and technological attributes [75].

5.2.3. Increased vitamins.

Human beings cannot synthesize sufficient levels of vitamins, but vitamins have a vital role in proper metabolic functioning. Their daily intake needs to be supplied with food that we consume. Maize grains have a very low concentration of vitamins (vitamins A and B12) and are deficient in amino acids (arginine and methionine). Various pretreatments like germination increased amino acids, vitamins, gamma-aminobutyric acid (GABA), and phenolic content [10,12,35]. Fermentation of maize by microbes also increases some of these compounds, including vitamins (i.e., thiamine, folate, riboflavin, vitamin c, and vitamin E) [10]. Some LAB species of genera *Lactobacillus* and *Lactococcu*s have been found to produce group B vitamins (B12, B11, and B2) [12]. On the other hand, yeast species of the genus *Saccharomyces, Kluyveromyces, Candida, Pichia, Torulaspora, and Issatchenkia* increased folate content significantly during fermentation. LAB contributes lower folate production as compared to yeast. However, a reverse effect on vitamin levels was also reported in maize-based traditionally fermented food - Ogi in which thiamine, riboflavin, and β-carotene were reduced by more than 65% [76]. The ability of vitamin production by yeast or LAB is strain specific. Some non-LAB microbes were also reported to improve amino acids and folate content during maize fermentation (i.e., *Bacillus licheniformis, Enterobacter cloacae*) [12]. So, these LAB can be added as starter or adjunct cultures to enhance food's nutritional and quality attributes. Furthermore, very meager literature is available on the studies for vitamin-E enhancement by bacteria and fungi.

5.2.4. Phenolic compounds.

Cereals are a good source of various phenolic compounds. The phenolics should be soluble to enter the blood circulation mechanism and extend antioxidant attributes in the human body. Various ways have been reported to increase the phenolics in food, like adding hydrolytic enzymes, fermenting LABs and yeasts, decreasing particle size, and germinating cereal grains [77]. The fermentation environment (temperature, incubation time, pH of finished product), type of microbial culture used, type of cereal, and grain are critical factors that decide the enhancement of phenolics [78].

Ogi (a traditional food of West Africa) prepared using sorghum and maize showed an increased concentration of total phenolic and flavonoid content with improved antioxidant activity [79]. Salar *et al*. (2012) reported increasing total phenolic content and radical scavenging activity in the maize by fermenting *Thamnidium elegans* CCF 1456. In this study, solid-state fermentation modulates the antioxidant capacity by releasing the bound phenolics present in untreated maize grains [80]. Fermentation induces several other metabolic pathways which could degrade and convert phenolic contents in high activity bioactive compounds such as catechin, gallic acid, and quercetin [81]. However, further research is needed to fully understand these and other microbially induced transformed metabolites.

5.2.5. Reduction of antinutrients-phytate.

Phytate (as myo-inositol 1,2,3,4,5,6-hexaphosphate), polyphenols, and tannins are antinutrients found in cereals and legumes. The phytates form a complex compound with minerals and inhibit enzymes, thus leading to decreased bioavailability and protein and carbohydrate digestibility [12]. Spontaneous maize fermentation can reduce a significant amount of phytic acid and improve minerals' bioaccessibility, as supported by various earlier studies [12]. Recently, Terefe *et al*. (2021) demonstrated that fermentation of maize by *Lactobacillus plantarum, Saccharomyces cerevisiae*, and co-culturing of both these species decreased antinutrient factors such as phytic acid, tannin, and trypsin inhibitor activity significantly. The authors reported that the highest decrease was observed in co-culture fermented products in which phytate (66%), tannin (75%), and trypsin inhibitor (64%) were reduced. Both species and their co-cultures were found suitable for preparing maize-based products to enhance nutritional attributes compared to traditional fermentation [70]. Gabaza *et* *al*. (2018) reported that phytate content decreased considerably (20% - 80%) after the fermentation of maize slurries collected in Zimbabwe [82]. The study also observed that iron and zinc bioavailability increases with reduced phytate content. Apart from LAB, *Bacillus* spp., *Pseudomonas* spp., and yeasts (*Pichia, Saccharomyces*, and *Candida*) also modify the bioavailability [83]. Hellström *et al*. (2012) reported a 95% decrease of phytates content in maize-based fermented product togwa, which was attributed to high phytase production by yeasts, particularly *Pichia kudriavzevii* TY13 and *Hanseniaspora guilliermondii* TY14[84].

5.2.6. Reduction of mycotoxin.

Some of the mold species of genera (e.g., *Aspergillus, Fusarium, Penicillium*, and *Alternaria*) can produce toxic secondary metabolites referred to as mycotoxin [85]. These mycotoxins are hazardous to humans and animals, can survive various processing treatments, and, therefore, are considered food safety hazards. Maize is a very sensitive cereal crop that is commonly contaminated with mycotoxins such as aflatoxin, zearalenone, cyclopiazonic acid, and fumonisins, but cereulide and patulin also were reported [86]. Different alternatives, such as fungicides and chemical preservatives, are used to overcome these problems and enhance shelf life. However, these unnatural ways of food processing can negatively affect the customer's mind as they are interested in natural, minimally processed, and safe products. In this regard, an alternative approach using microbial cultures, cell-free supernatant, or extracted compounds showing antifungal properties is gaining interest.

Several studies have been conducted to evaluate the antifungal activities of different microbes, including Lactic Acid Bacteria, in different food products. LAB has been tested in dairy and bakery products as a bio-preservative to control fungal growth. The microbes have also been studied for their antifungal properties in fermented vegetable products and to protect stored grains and seeds. Maize grains are susceptible to mycotoxin contamination during production and storage [87]. Therefore, various alternative processing strategies, including fermentation, are applied to control mycotoxin [86]. Recently Ademola *et al*. (2021) demonstrated that Lactic acid bacterial fermentation in maize-based product Ogi decreased aflatoxins and fumonisins in the commercial processing plant of Nigeria [56]. In a similar study, there was a significant reduction (about 90%) of mycotoxins compounds due to steeping/fermentation of maize-based ogi [88]. *Lactobacillus plantarum* LUHS135 and *Lactobacillus paracasei*LUHS244 from fermented cereals were isolated and reported to be effective mycotoxin inhibitors - “aflatoxin B1, ochratoxinA, HT-2 toxin, T-2 toxin, zearalenone” [89] and in another study, commercial LAB strains were reported to reduce maize silage mycotoxin [90]. Furthermore, some non-LAB species, such as *Bacillus subtilis*, also reported degrading zearalenone in liquid broth [86].

The fermented maize products were also studied for single culture and mixed culture activity (Yeast + LAB) to control the mycotoxin production. The various studies reported that mycotoxin degradation could be achieved by LAB and yeast; however, their degradation ability could be strain-specific and require synergistic activity with other stains [86]. Moreover, it can be concluded that LAB strains can be deliberately added as an efficient detoxifying agent in maize fermentation.

5.3. Improved sensory and organoleptic properties.

The food products are primarily judged based on sensory and Organoleptic attributes [91]. The cereal fermentation by LAB and yeasts produces various volatile and non-volatile flavoring compounds through a series of biochemical pathways [92]. These flavoring compounds produced by potential microbial strains are considered safe. They have appealing flavors and aromas, which is important to select any LAB strain as a probiotic for cereal fermentation.

5.4. Production of exoploysachharides.

The production of exopolysaccharides (EPS) is an important desirable property to improve the textural attributes of cereal-based fermented foods without any safety concerns [93]. Several reports demonstrated and explored the amylolactic and exopolysaccharides producing bacteria and yeasts isolated from the cereal-based products (Manini, 2016). The Exopolysaccharide (EPS) producing ability of the bacterium *Weissella confusa* C19 was assessed during the manufacturing of boza using different cereals (maize, oat, rice, and wheat). The rheological attributes of EPS produced in these different cereal matrices showed that the steady shear behavior of EPS was pseudoplastic [94]. EPS production of *Lactobacillus* plantarum isolated from “Nigerian traditional fermented cereal gruel ogi" was investigated by Fourier-transform infrared spectroscopy, and the EPS production for tested strains was found in the range of 1.36 g/L to 2.18 g/L [95]. In a similar study, thirteen LAB strains isolated from Boza were evaluated for EPS production and potential use as an adjunct culture, in which most strains showed significant EPS production[96]. The production of EPS in foods provides various benefits to living beneficial bacteria, like protection from adverse conditions, toxic molecules, phagocytosis, biofilm formation, and cell recognition [97]. Various structures of EPS perform different roles in EPS-producing cells, which are still unknown and mostly strain-dependent [98].

5.5. Health benefits of maize-based fermented foods.

5.5.1. Potential role of maize-based fermented foods in preventing diseases.

The consumption of fermented products is reported to prevent and treat diseases such as lactose intolerance, vaginitis, colorectal cancer, hyperlipidemia, oxidative stress, irritable bowel syndrome, and intestinal infections [34,99]. Some *Lactobacilli* probiotic strains have decreasedHelicobacter pylori infections linked to stomach cancer [100]. Another study on patients with persistent human papillomavirus (HPV) found that daily probiotic consumption for six months improved HPV and cervical cancer precursor clearance [101]. The exact mechanism underlying probiotics' anticancer effects is unknown. The gut microbiota is involved in several pathways, which are supposed to play a vital role in fermentation. The probiotic LAB associated with maize-based foods and beveragesis primarily involved in preserving homeostasis or maintaininga stable physicochemical environment in the colon. Increased acidity, which can be generated by an excess of bile acids in feces, could be a direct cytotoxic factor impacting the colonic epithelium, leading to colon cancer [102]. The use of probiotic bacteria such as *Lactobacillus acidophilus* and *Bifidobacterium bifidum* is a promising strategy in cancer prevention due to their involvement in modulating pH and bile acid profile [102,103].

5.5.2. Anticholesterimic activities.

Cardiovascular diseases are one of the significant causes of death in adults globally and are often associated with higher serum cholesterol levels. The consumption of LAB with fermented foods can reduce serum cholesterol levels, and numerous reports claim this combination's hypocholesterolemic effect. Recently many studies also explored the anticholesterimic potential of LAB isolated from different fermented products. Recently, *Pediococcus pentosaceus* OBK05 strain isolated from fermented products was evaluated for probiotic attributes, including cholesterol reduction ability *in vitro* studies [104]. Another report demonstrated that *Lactobacillus fermentum* strains (PD2 and PH5) isolated from a traditionally fermented food product, were exhibited good anticholesterimic activity (reduction in serum cholesterol, LDL-cholesterol, and TG concentrations) in mice in comparison to mice fed with a control diet (same high cholesterol diet) but without adding *Lactobacillus* strains [105]. *Lactobacillus fermentum* MJM60397 reduced the concentration of total cholesterol and LDL and was reported to significantly reduce the levels of total cholesterol and low-density lipoprotein (LDL) in rats due to its ability to deconjugate the bile salt [106]. A similar study reported that *Lactobacillus helveticus* strains KII13 isolated from fermented products reduced the cholesterol in an animal model (mice) study [107]. They demonstrated that this strain has the potential to form antihypertensive peptides and decrease serum cholesterol.

5.5.3. Production of antimicrobial compounds.

The fermentation process produces antimicrobial substances, such as organic acids (e.g., acetic acid, lactic acid, propionic acids, and acetic acid), H_2O_2, free fatty acids, ammonia, biosurfactant, and peptidic structures known as bacteriocin. Bacteriocins are inhibitory to various types of gram-positive bacteria. Recently, Heidari *et al*. (2022) reported inhibitory activity of *Lactobacillus curvatus*LAB-3H against food-borne pathogens(*L.monocytogenes,B. cereus, S. aureus*, and *E. coli*) due to lactic acid production and other antibacterial substances [108]. The production of various organic acids causes the lowering of the pH, which causes acidification of the cell cytoplasm resulting in disruption of electron transport systems of invading pathogens [109]. Some LAB species also produce considerable fatty acids, such as Reuterin, which have been reported to show antimicrobial activity in a controlled environment [110]. Queiroz*et al*. (2022) demonstrated the bacteriocins-producing ability of the isolates ("*Pediococcus pentosaceus* ST75BZ, *Pediococcus pentosaceus* ST87BZ, and *Pediococcus acidilactici* ST31BZ") obtained from Boza, which was found effective against certain pathogens such as *L. monocytogenes*[111]. The bacteriocin-producing strain (*Lactobacillus fermentum* O3) was isolated from ogi and characterized the antimicrobial properties against various food-borne pathogens [112]. However, further characterization, clinical trials, validation, and safety evaluation are needed before use in product formulation.

5.5.4. Production of bioactive compounds.

Fermented foods attracted the interest of the scientific community and industry due to their ability to produce various bioactive compounds, which may be microbial cells or metabolic modified products of cereal fermentation. Several studies demonstrated the beneficial effects of these bioactive components, like control and management of mutagenesis, carcinogenesis, pathogenicity, diabetes, cholesterol accumulation, and immunomodulatory properties [113]. Some strains reported producing γ-aminobutyric acid (GABA), which improves cardiovascular functionality as a bioactive compound in fermented cereal products [114]. The potential of LAB strains was also explored for producing bioactive fatty acids like conjugated linoleic acid and conjugated linolenic acid in cereal-based fermented foods [115].

6. Effect of Maize Components on Probiotic Growth

The cereals, including maize, contain different potential prebiotic compounds such as resistant starch, β-glucans, arabinoxylans, phenolic substances, oligosaccharides, polypeptides, and other constituents. The potential prebiotic effect of these components depends on the type of cereal used and the extent of fermentation that occurred; however, the component-specific effect could be investigated and corroborated through scientific studies [116,117]. Although there are very few reports on the prebiotic potential of cereal-based fermented products, some recent studies show that cereal components significantly impact gastrointestinal microflora. The effect of β-glucans and how Bacteroides behaved in the human gut was studied, and reported these compounds are important for gut microbial metabolism [118]. Recently, a study reported the extraction of arabinoxylans from different cereals and their impact on the growth of bacteria [119]. The prebiotic effect of maize containing high resistant starch (Hi-maize) was also evaluated for moist and freeze-dried microparticles of *Lactobacillus acidophilus*. The study reported that hi-maize (used at1% concentration) provides better protection during in-vitro simulated gastrointestinal environment and storage at room temperature (25 °C) [120].

7. Conclusion and Future Perspective

Various scientific studies revealed that natural fermenting microflora induces a series of biochemical pathways during maize fermentation that lead to the formation of a wide range of beneficial metabolites, which could be accessible to all community members. These changes positively affect the nutritional, textural, and sensory quality of products, improve vitamin and mineral bioavailability, and control undesirable pathogenic microflora. However, uncontrolled microbial interaction in spontaneous fermentation of maize is not always generate consistent quality products, and attributes vary with fermentation environment, types of strain/species, raw grain quality, and presence of competing microflora.

The increasing acceptance of traditionally fermented food will keep attracting the scientific community's and commercial industry's attention to improve the nutritional attributes, shelf life, and sensorial quality of existing products**.** Rapid urbanization, population explosion, increased purchasing power, and health awareness among consumers provides an opportunity for policymakers of Asia and Africa to develop maize-based products as health formulae to feed the malnourished population of these areas. Maize is deficient in some important proteins that can be transformed and modified by microbial fermentation and blending with other easily available nutrient-rich cereals, legumes, and vegetables to obtain nutritionally superior maize-based products. The maize-based fermented products are indigenously fermented, and very few efforts have been made to commercialize them. Some manufacturers tried maize-based pozol, boza, ogi, and bread but could not produce them in large-scale industries due to limited shelf life and lack of typical flavor and taste characteristics. Modern biotechnological techniques and metagenomics approaches could be used to develop novel strains to enhance the nutritional quality of maize-based foods. Further, more research needs to be done to explore the probiotic potential of native microflora and a better understanding of microbial interactions that shape and decide the composition, metabolite diversity, and nutritional aspect of maize fermentation as a primary function keeping in view the process improvement and human health.

Funding

The author(s) received no financial support for this article's research, authorship, and/or publication.

Acknowledgments

This research has no acknowledgment.

Conflict of Interest

The authors confirm that they have no conflicts of interest concerning the work described in this manuscript.

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