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Nutritional Value and Consumer Acceptance of Non-Alcoholic Cereal-Based Beverages in Sub-Saharan Africa: A Review of Fortification, Supplementation, and Processing Innovations

MMAPHUTI ABASHONE RATAU[1]*, OLUWASEUN PETER BAMIDELE[1], VICTORIA ADAORA JIDEANI[2] and SHONISANI EUGENIA RAMASHIA[1]

[1]Department of Food Science and Technology, University of Venda, Thohoyandou, South Africa.
[2]Department of Food Science and Technology, Cape Peninsula University of Technology, Bellville, South Africa.

Abstract

Non-alcoholic cereal-based beverages (NACBs) are important to the cultural traditions of sub-Saharan Africa (SSA), as each region uses locally grown cereals to create unique beverages. However, they are often seen as inferior to dairy products due to their lower protein content (1-3%) and lysine levels (0.18-3.38%), compared to dairy, which contains 3-4% protein and 7.50-8.20% lysine, along with the presence of anti-nutrients. This review reveals recent advancements in food fortification, supplementation, and processing innovations that enhance the nutritional value of these beverages while addressing sensory characteristics that influence consumer preferences. An overview literature analysis from the past decade (2015-2024) was conducted on supplementation and fortification techniques, processing methods, and health benefits of NACBs while highlighting their cultural significance and production processes. Additionally, the review highlights these techniques' potential health, economic, and social advantages. While fortification and supplementation can significantly enhance the nutritional profile of NACBs, they may also alter taste, potentially leading to decreased consumer acceptance. For example, NACB, with 5% of the whole moringa, scored 4.33 versus 7.62 for the control beverages. There is a pressing need for ongoing research to identify effective fortificants and supplements that improve taste without compromising nutritional benefits. Enhancing the sensory appeal of fortified NACBs can address nutrient deficiencies and positively influence public health and economic participation in SSA. Overall, these efforts hold significant promise for improving the health and well-being of populations across the region.

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CONTACT Mmaphuti Abashone Ratau mmaphuti.ratau@univen.ac.za Department of Food Science and Technology, University of Venda, Thohoyandou, South Africa.

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Abbreviations

Non-alcoholic cereal-based beverages: NACBs
Sub-Saharan Africa: SSA

Introduction

Nutritional deficiency affects over one-third of the global population, with one in four individuals in sub-SAharan Africa (SSA) experiencing hidden hunger.[1,2] Iron, zinc, and vitamin A deficiencies pose significant global health issues, with SSA accounting for 80% of these instances, resulting in elevated rates of illness and death among children and pregnant women.[3] Over 2 billion people worldwide are estimated to lack essential micronutrients, predominantly impacting low-income countries where access to nutrient-dense foods is restricted.[4]

Hidden hunger is a serious yet often overlooked form of malnutrition characterized by a lack of essential vitamins and minerals despite adequate caloric intake.[1,2,5] This condition primarily stems from food insecurity, heightened nutritional demands during critical life stages,[2] and a preference for energy-dense but nutrient-poor foods.[6] Additionally, health issues can impair nutrient absorption (malabsorption),[7] and a general lack of awareness regarding the importance of micronutrients intensifies the situation. The economic repercussions are significant, with hidden hunger contributing to an estimated 2 to 5% GDP loss, equating to approximately $20 to $30 billion annually.[8]

Strategies such as dietary changes, food fortification, biofortification, and supplementation are essential to combat these challenges.[9,10 11] Food supplementation and fortification are affordable strategies to combat malnutrition in developing countries.[10] Food supplementation provides high doses of specific micronutrients such as iron, iodine, and vitamins A and D.[12,13] In contrast, food fortification enhances the nutritional content of widely consumed staples such as salt and flour.[14,15] Approximately 140 countries have implemented fortification programs, yielding notable health benefits, including a 34% reduction in anemia and a 41% decrease in neural tube defects.[16] However, the full potential of these initiatives remains untapped in SSA, where hidden hunger persists.[16]

Africa's rich cultural heritage includes diverse traditional fermented non-alcoholic cereal-based beverages (NACBs), which are gaining popularity for their convenience and nutritional density.[17] The demand for functional beverages such as NACBs that promote mood, energy and general well-being has led manufacturers to explore lower-sugar options and incorporate beneficial ingredients such as vitamins, adaptogens, plant-based ingredients and probiotics.[18–20] Advances in production technology facilitate the integration of non-soluble functional ingredients. The coronavirus disease 2019 pandemic has further accelerated this trend, with the non-alcoholic beverage market projected to grow at an annual rate of 6.8%, reaching over 935 000 million liters by 2025.[18] However, specific figures for non-alcoholic cereal beverages in SSA are unavailable.

Despite their health benefits, NACBs can contain anti-nutrients and suffer from poor digestibility.[21] Processing techniques such as soaking, milling, cooking, roasting, malting, and fermentation are employed to enhance the organoleptic nutritional value and extend the shelf life of NACBs.[22–24] However, while fermentation is cost-effective, it can also lead to harmful microorganism growth, such as yeast and molds, if not managed properly.[22]

Regular consumption of NACBs without nutrient enhancement can lead to deficiencies,[25] therefore, fortifying these staple foods with essential nutrients is crucial for improving health outcomes.[15,26] This approach not only preserves traditional practices but also meets dietary needs effectively and can boost the economy and reduce food and healthcare costs.[27] Fortification has proven successful in enhancing nutrition while generating economic benefits; for instance, iodizing salt costs approximately $0.12 per person annually but yields a return of over $26 for every $15 invested.[15]

Research indicates that supplementation and fortification can significantly improve the nutritional profile of traditional beverages. For example, sorghum-*Mahewu* supplemented with Bambara groundnut has shown improvements in essential amino acids and protein content.[28] *Moringa oleifera* leaf powder enhanced calcium, iron, ash, fat, and fiber in *Mahewu*.[26,29] Additionally, lipid-based nutrient supplements have effectively addressed malnutrition issues in children by reducing stunting by 12-14%, anemia by 16%, and iron deficiency anemia by 64% among children aged 6-24 months.[30]

This review examines the benefits and challenges of supplementing or fortifying non-alcoholic beverages in SSA while discussing modern processing techniques that enhance these products' nutritional value. Recommendations for future research are also provided to address existing gaps in knowledge and practice. By leveraging these strategies, we can combat hidden hunger and improve public health outcomes across vulnerable populations in SSA.

Aims of the Review Article

The review aimed to evaluate various supplementation and fortification techniques for enhancing NACBs examine current production practices, and investigate the health advantages of these beverages. It also aimed to highlight the cultural importance of NACBs and highlight new technologies that could boost their nutritional content and functional benefits. Furthermore, the article stresses the necessity for additional research to refine production methods and tackle nutrient deficiencies in these beverages.

Methodology

In 2024, an overview of literature review was carried out and updated in early 2025, mainly using Google Scholar to analyze studies from the last decade (2015-2024) related to fortification techniques, processing methods, and health benefits of NACBs in SSA. The review included English-language articles exploring fortified or supplemented cereals' nutritional and sensory properties. It also investigated the microorganisms involved in fermentation, the challenges that fortification and supplementation aim to overcome, and their effects on micronutrient deficiencies. Key cereals included millets, sorghum, barley, rice, and maize. Furthermore, the research investigated modern processing techniques designed to enhance the quality and safety of NACBs. The search employed keywords such as non-alcoholic cereal beverages, SSA, fortification, supplementation, modern processing methods, nutrition, economy, micronutrient deficiency, starter culture, and benefits. The results were compiled to highlight gaps in future research that need to be addressed.

General Overview of Non-Alcoholic Beverages in Sub-Saharan Africa

Advancements in Non-Alcoholic Beverages in Sub-Saharan Africa

Over the past decade, the landscape of NACBs in SSA has undergone significant transformation, marked by improved nutritional profiles and cultural relevance. This evolution is characterized by incorporating diverse ingredients, fortificants, and supplements aimed at enhancing the health benefits of these beverages. NACBs are not only a staple in the diets of many communities but also play a crucial role in cultural practices across the continent.[17] Their consumption has been linked to various health benefits, including enhanced metabolism, improved gut health, and potential anti-inflammatory properties.[23,31,32]

Nutritional, Health and Cultural Significance of Non-Alcoholic Beverages

Traditional NACBs such as *Ogi* and *Mahewu* serve essential functions in infant nutrition, aiding in weaning and gastrointestinal health, while *Mursik* contributes to maternal and fetal well-being during pregnancy.[25,33] Additionally, beverages like *Koko* exhibit antibacterial properties against pathogens such as *Salmonella* and *Escherichia coli*,[34] and *Nunu* is recognized for its immune-boosting effects.[33] The detoxifying capabilities of these beverages highlight their multifaceted contributions to community health, offering a convenient means for individuals to integrate vital nutrients into their diets.[31]

The Role of fermentation of Non-Alcoholic Beverages

Fermentation is crucial in enhancing the nutritional quality of traditional cereal-based beverages. This process involves microorganisms that break down complex carbohydrates and proteins, which enhances the bioavailability of nutrients and facilitates better absorption of essential nutrients. Throughout fermentation, a range of metabolites is produced that enhance sensory qualities and provide notable health benefits, such as probiotic, antioxidant, and antimicrobial properties.[21,35,36] Such properties are crucial for managing chronic diseases, including cardiovascular issues, cancers, diabetes, allergies, and gastrointestinal disorders that account for approximately 41 million deaths globally, representing 74% of all fatalities.[37]

Fortification and Supplementation Strategies

Fortification and supplementation are increasingly employed to further enhance the nutritional value of NACBs. Fortificants and supplements can be classified into three categories: natural fortificants, which include items such as groundnuts, termites, beetroot, aloe, and sweet potatoes; mineral fortificants, such as ferrous sulfate, zinc, and calcium; and modern fortificants, which consist of vitamins and omega.[28,38–40] Fortification and supplementation address nutrient deficiencies by incorporating essential vitamins and minerals into NACBs. For instance, fortifying *Mahewu* with ferrous sulfate significantly boosts its iron content, addressing prevalent deficiencies in regions such as Mozambique.[40] Similarly, blending Bambara groundnut with sorghum beverages enhances protein levels (6.09-7.65%), crude fiber (5.68-7.88%), and essential amino acid (such as 175.97-

278 lysine, 174.23-237.42 threonine, mg/100 g) profiles critical for infant nutrition, while reducing the phytates from 99.82-22.82 mg/100 g.[28]

Table 1 shows the various fortified and supplemented non-alcoholic fermented beverages from SSA, detailing their ingredients, added nutrients, cultural significance, and health benefits. Noteworthy examples include fortifying cassava-based beverages in Nigeria with winged termites, which has improved crude protein (19.22-22.46%) and micronutrient content, including iron (by 47%), zinc (by 69.46%) and calcium (by 67.51%), thereby enhancing the nutritional value of these traditional complementary beverages.[39] Moreover, incorporating moringa into maize and sorghum *Mahewu* beverages has significantly boosted calcium (0.02-0.22 mg/100 g), iron (33-100.4 mg/100 g), and other essential minerals, contributing to better overall health outcomes.[26,29]

Additionally, adding 2% aloe vera to *Mahewu* extended its shelf life from 4 to 15 days, although the taste of the modified beverages was not well received.[38] These examples highlight the potential of fortification strategies to transform traditional beverages into nutrient-rich options that effectively combat malnutrition and support public health initiatives in vulnerable communities. While fortification has yielded positive outcomes, it is essential to recognize potential drawbacks. Some fortified beverages have exhibited increased sodium levels or altered fat content, raising concerns about cardiovascular health risks.[41,55] Moreover, not all studies have reported favorable results from these interventions.

The advancements in non-alcoholic beverages within SSA reflect a dynamic interplay between traditional practices and modern nutritional science. By embracing fortification strategies that utilize both natural ingredients and innovative techniques, there is significant potential to combat malnutrition while promoting public health initiatives. A balanced perspective on both the successes and challenges associated with these developments will foster a deeper understanding of how traditional NACBs can evolve to meet contemporary health needs effectively.

Production process of Non-Alcoholic Cereal Beverages

The production of non-alcoholic beverages in SSA involves various methods that reflect different regions' cultural diversity and culinary traditions.[24] The primary and secondary ingredients used in fermented beverages result in unique sensory characteristics in each region. For example, *Kunu*, a popular Nigerian beverage, can be made from millet, sorghum, or a combination of grains, with different regions adding various flavorings and sweeteners such as ginger, cloves, sugar, commercial sweeteners, and red or black pepper.[56] Similarly, *Mahewu*, found in southern Africa, can be made from either sorghum or maize.[29,31] Production methods vary slightly by region, with ingredient preferences being the main difference; in West Africa, millet and sorghum ingredients are often split into unequal parts, with the larger portion cooked with hot water to gelatinize starch before fermentation with an inoculum.[56] In southern Africa, leftover maize porridge is typically used to produce *Mahewu* or a similar method that involves thin-cooked porridge in West Africa is followed. In contrast, *Ogi* can be produced from wet millet flour, which is filtered, and the filtrate is left to ferment to produce *Ogi*,[31] Fermentation times also vary, lasting from 24 to 48 hours, and can extend up to five days, depending on the desired sourness.[31,53] These traditional techniques have been passed down through generations and involve several key steps, such as sourcing and handling raw materials, treating the raw materials, extracting, fermenting, flavoring, straining, and packaging/serving.[17,24,57]

The generic production process begins with locally grown grains such as sorghum, maize, or millet, which are collected and cleaned by removing debris. The grains are soaked in water at 25-30 °C for about 6-24 hours to aid in swelling and digestibility.[58] This soaking process is crucial in the subsequent malting process, as it kickstarts germination and alters the endosperm structure of the grains. The grains are then malted for 48 to 72 hours, sun-dried for 5 to 20 hours, and milled.[19] During malting, the moist grains are spread out to germinate before being manually ground into flour for use.[59] Maize, millet, and occasionally cassava are common grains used for malting. The primary purpose of malting is to activate hydrolytic enzymes that are not present in raw grains. Kilning comes after malting and halts embryo growth and enzymatic activity while preserving enzyme function.[59] Modern methods involve kilning the grains between 40 and 220 °C depending on the produced malt.[60,61] Elevated kilning temperatures (50-60 °C) have been linked to reduced grain starch and sugars, along with increased protease activity.[60] Nonetheless, these higher temperatures (2 hours kilning, 210 °C) may also lead to the formation of carcinogenic polycyclic aromatic hydrocarbons in some dark roasted malts.[61]

Table 1: Enhanced non-alcoholic fermented beverages, their fortificants/supplements, and nutritional impacts

Non-Alcoholic Beverage	Key Ingredient	Fortificants/ Supplement	Region/Country of Origin	Traditional/Cultural Significance	Outcome of enhancement	References
Mahewu/Mageu	Cassava (*Manihot esculenta*)	Ferrous sulphate and ferrous fumarate	Mozambique	A popular traditional fermented drink	Higher iron content	[40]
	Sorghum (*Sorghum bicolor* L. Moench)	Bambara groundnut (*Vigna subterranea*)	Southern Africa		Higher protein and crude fiber, increased mineral and essential amino acid contents	[28]
	Cassava (*Manihot esculenta*)	Beetroot (*Beta vulgaris* L)	Mozambique	Refreshing and weaning drink	Improved levels of iron, potassium, sodium and zinc	[41]
	Maize (*Zea mays*) and wheat (*Triticum aestivum* L.)	Aloe vera (*Aloe barbadensis*)	South Africa	Weaning foods and adult's dietary staples	Not determined	[38]
	Maize (*Zea mays*)	Watermelon (*Citrullus lanatus*)	Southern Africa	Energy, thirst-quenching beverage for all age groups, including by weaning infants.	Better protein, ash, vitamin C, and total carotenoid contents	[42]
	Maize (*Zea mays*) and sorghum (*Sorghum bicolor* L. Moench)	Flaxseed (*Linum usitatissimum*) and soybean (*Glycine max*)	Southern Africa	Weaning food for infants	Improved crude protein, fat, micronutrients, phenolic content and antioxidant activity	[10]
	Cassava (*Manihot esculenta*)	Winged termites (*Macrotermes nigeriensis*)	Nigeria, West Africa	Complementary drink	Improvement in crude protein, fiber, fat, and ash. A decrease in carbohydrate. Increase in	[39]

		iron, zinc, vitamin C and			riboflavin.	
	Orange maize (*Zea mays*)	*Lippia javanica*	Southern Africa		Improved total polyphenols, total antioxidant activity, iron, magnesium and zinc.	43
	Maize (*Zea mays*)	Moringa (*Moringa oleifera*)	South Africa	Thirst quenching, hunger filling and convenient and refreshing, weaning	Higher in fat, fiber, crude protein, calcium, iron, copper, manganese, potassium and magnesium	44
	Sorghum (*Sorghum bicolor* L. Moench)	Moringa (*Moringa oleifera*)	South Africa		High protein, ash and fibre, minerals and amino acid contents	29
Sorghum beverage	Malted sorghum (*Sorghum bicolor*)	Cocoa (*Theobroma cacao*)	Nigeria, West Africa		Improved calcium, magnesium, potassium and zinc, except phosphorus.	45
Kunun-zaki	Pearl millet (*Penni -setum glaucum*)	Groundnut (*Arachis hypogea*)	Nigeria, West Africa	Body fluids and nutrients that refresh and nourish	Increased the composition of protein, ash, and crude fat. Decreased crude fibre content	46
	Groundnut (*Arachis hypogea*)	Rice (*Oryza sativa*), sesame seeds (*Sesamum indicum* L.), sprouted soybean (*Glycine max*)	Nigeria, West Africa	Child Nutrition	Increased protein content	47
Kunun-zaki	Millet (*Panicum miliaceum*)	Tigernut (*Cyperus esculentus Lativum*)	Nigeria, West Africa		Improvement in thiamine and riboflavin contents. Higher sodium, calcium,	48

					potassium, magnesium, phosphorus and iron.	
	Millet (*Panicum miliaceum*)	Orange fleshed sweet potato (*Ipomoea batatas*)	Nigeria, West Africa	Refreshing drink	Replacement of sugar, possibly increased vitamin A content	49
	Millet (*Pennisetum typhoideum*)	Serendipity berry (*Dioscoresphyllum cumminsii*), defatted *Moringa oleifera* seeds	Nigeria, West Africa	Appetizer	Increased protein and reduced fat. Higher potassium, calcium, and copper.	50
	Sorghum (S*orghum bicolor L. Moench*)	Orange-flashed sweet potato (*Ipomoea batatas*)	Nigeria, West Africa	Thirst quenchers	Improvement in carotenoids and vitamin A. Reduction in tannins,	51
	Pearl millet (*Pennisetum glaucum*)	African locust bean (*Parkia biglobosa*)	Nigeria, West Africa	Serves as thirst-quenching and complimentary food beverage.	Increased crude fibre, total ash, phosphorus, potassium, vitamin A and phytochemical contents except for phytate.	52
Pearl millet beverage	Pearl millet	Moringa (*Moringa oleifera*)	South Africa		Increased protein and decreased fat content	53
Ogi	Sorghum	Cocoa (*Theobroma cacao*)	Nigeria, West Africa		Increase in zinc, potassium, iron, calcium, magnesium,	54

The next step, mashing, typically lasts 5 to 10 hours[23] and involves extracting fermentable sugars, amino acids, and vitamins from the malt.[62] In the traditional method, starch is extracted to act as a sugar source to aid fermentation and to add body to the beverage. Non-alcoholic beverages traditionally undergo natural fermentation on sunny days at 20-30 °C for 24 to 72 hours, depending on the region, driven by microorganisms in the ingredients.[31] This fermentation happens spontaneously, possibly introducing food safety and quality issues due to unwanted microorganisms.[24,31,56] The resulting beverages tend to be acidic, with pH levels ranging from 2.93 to 5.30, contributing to their unique flavors and overall quality.[23] To mitigate potential issues, some suggested interventions include using sterile equipment and introducing starter cultures to help regulate fermentation.[24,53,56] Alternatively, back-slopping is a standard fermentation method where a previously used container, such as clay pots or calabash, is used without washing to carry out fermentation.[17] Microorganisms from the previous batch aid fermentation. Natural fermentation, typically led by lactic acid bacteria and yeast strains, contributes to the unique flavors of the beverage. *Enterobacteriaceae* are bacteria commonly found in plants that initiate the fermentation process.[17] These bacteria thrive in environments with limited oxygen and are particularly abundant in cereal grains. Following the growth of *Enterobacteriaceae*, other bacteria such as *Pediococcus, Enterococci, Lactococci, Leuconostoc,* and *Weissella* species also contribute to the fermentation process.[17,24,53]

Traditional non-alcoholic beverages are commonly made and stored in earthen pots and calabashes instead of stainless steel or aluminium containers, which tend to be colder and may delay fermentation.[25] After fermentation, the drinks are filtered, flavored, sweetened, and strained through cheesecloth before being packaged for sale or serving. Unwanted microorganisms can speed up spoilage after fermentation, mainly if there is a long delay between production and consumption, posing food safety risks and leading to early spoilage.[53] Beverages stored in calabashes and earthen pots often have better sensory qualities than plastic containers, which are generally not preferred.[25] However, used soda bottles are sometimes utilized in informal trading. Due to a lack of refrigeration, these drinks are typically kept in cool areas like round mud huts,[25] allowing them to last 3 to 5 days.[31] The beverages are susceptible to excessive sourness from extended fermentation during storage, which has decreased their popularity, particularly for *Mahewu*.[21] In some improved production methods, pasteurization and chemical preservatives are commonly used.[23]

Microbial Diversity of Non-Alcoholic Beverages for each Region in Sub-Saharan Africa

The microbial diversity found in traditional NACBs in SSA, such as *Kunu*, *Mahewu*, and *Ogi*, features a rich complex of lactic acid bacteria, yeasts, and molds that impart distinctive flavors, aromas, and health benefits to these fermented beverages. Various microorganisms, including *Lactobacillus species, Aerobacter, Saccharomyces cerevisiae, Bacillus subtilis,* and *Staphylococcus aureus*, have been identified across different SSA regions, including Eastern, Western, Central, and Southern Africa (Figure 1).[17,23,33]

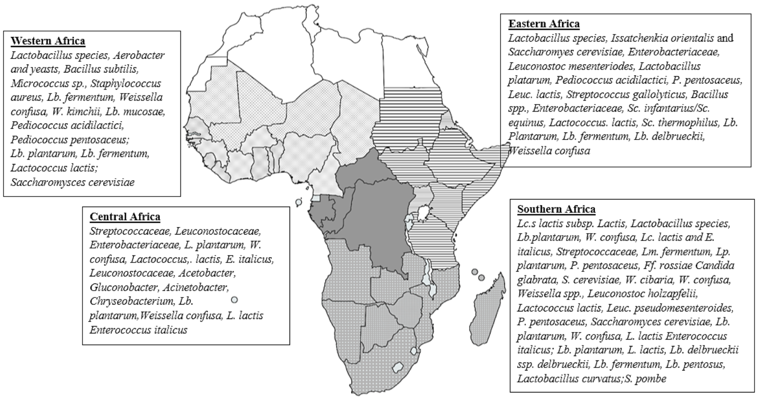

Fig. 1: Microbial diversity of non-alcoholic beverages in sub-Saharan Africa by region.[17,23,31,33]

Other notable microorganisms include *Weissella confusa, W. kimchii, Pediococcus acidilacti, Pediococcus pentosaceus,* and *Lactococcus lactis*, alongside important bacteria like *Lb. plantarum, Lb. fermentum, and Lb. mucosae*, as well as yeasts such as *Issatchenkia orientalis*.[17,23,31,33] Despite thorough investigations into the microbial profiles of these beverages, there remains a scarcity of commercially available starter cultures that can reproduce the unique sensory characteristics of household-produced beverages.

For example, *Mahewu* has a creamy, sour taste with fruity banana notes produced by yeasts such as *Saccharomyces cerevisiae.* It also contains lactate and amino acids from bacteria such as *Lactococcus lactis* and *Lactobacillus* species.[21,63] *Bushera* made from sorghum, popular in Uganda, has a sweet-to-sour taste from lactate and acetate due to heterotactic lactic acid bacteria such as *Lactobacillus* plantarum and *Lactobacillus fermentum*.[23,64] *Koko* from millet, a West African drink, features a sweet-sour flavor contributed by non-volatile lactate from homolactic lactic acid bacteria.[21]

Other bacterium, such as *Lactobacillus fermentum* LB-11, produce metabolites like lactic, acetic, and propionic acids during maize fermentation.[21] These metabolites contribute to unique sensory traits like sour and pungent aromas. It also produces volatile compounds like carboxylic acids and alcohols, giving distinctive odors like burnt rubber and fruity. Other strains like *Lactobacillus pentosus, Lactobacillus plantarum, Pediococcus acidilactici, Pediococcus pentosaceus,* and *Lactobacillus fermentum* also contribute to cereal fermentation, generating metabolites like acetic acid that add sourness and buttery flavors.[21]

Modern Processing Techniques to Produce Non-Alcoholic Beverages

The traditional method of producing NACBs in SSA remains a simple household art,[65] as shown in Section 2.5. NACBs, such as *Mahewu, Ogi, Kunun,* or *Bushera*, vary based on region, culture, and the raw materials and methods used in their production. As urbanization continues in SSA,[66] there is a significant shift from traditional diets to Western-style eating patterns prioritizing calorie-dense foods high in animal protein, fats and sugars.[67] This change, alongside a rising awareness of health issues, has led to a greater demand for NACBs, as consumers look for healthier options compared to dairy and alcoholic drinks. The coronavirus diseases 2019 pandemic has sparked interest, particularly in NACBs fortified with probiotics and vitamins (A, D and E) that promote immune health.[18,68] The global probiotics market, valued at $68.56 billion in 2022, is expected to grow to $133.92 billion by 2030.[36] In response to this increasing demand, there are initiatives to improve traditional NACBs processing methods with modern techniques to satisfy the changing tastes of health-conscious consumers in a more urbanized setting.

Different methods and technologies could be used to modernize the production of NACBs on a larger scale. These modern methods aim to improve the overall quality of the NACBs by optimizing factors such as the raw material selection, fermentation and post-fermentation treatment and storage conditions. One key aspect of producing high-quality, non-alcoholic beverages is selecting and preparing raw materials.

Thorough cleaning processes are essential for removing impurities and ensuring final product purity.[69] Conditioning the grains with water can also enhance the milling process and improve the overall quality of the beverages.[23] Modern techniques like ultrasonication, which have shown promise in increasing the total phenolic content (10.65-11.22 mg GAE/100 g), total flavonoid content (3.64-9.74 mg QE/100 g) and antioxidant properties (17.05-22.73%) of NACBs, offer a bright future for the health benefits of these beverages.[70] These increased phenolic content, total flavonoid, and antioxidant properties, with their potential to contribute to the prevention of chronic diseases and the promotion of overall health, are promising prospects for health-conscious consumers.[71] Enzyme treatments, fortification, and supplementation have also been utilized to enhance the nutritional value of NACBs made from cereals such as millet, sorghum, and maize.[31]

The natural fermentation of cereal grains can reduce essential nutrients, including carbohydrates, crude protein, crude fat, and certain minerals, which may result in nutrient deficiencies.[23,72,73] The natural fermentation of cereal grains can reduce essential nutrients, including carbohydrates, crude protein, crude fat, and certain minerals, which may result in nutrient deficiencies.[23,72,73] For example, spontaneous fermentation of maize ogi flour at room temperature for 72 hours caused a percentage reduction of 15-24% in crude protein, 4.6-18% in fat, 27.32% in ash, 46-49.2% in crude fiber, and 21-96% in minerals.[74] Similarly, the fermentation of pearl millet flour at 28 °C for 72 hours resulted in a 24% reduction in crude fat and a decrease in minerals (ash) by 2-43%.[74]

Additionally, natural fermentation of sorghum for 48 hours at room temperature led to reductions in fat (2.5-16% reduction), fiber (20.8-40.4% reduction), carbohydrates (0.32-1.4% reduction), and most minerals (0.02-7.2% reduction).[74] To counteract these losses, nutrients from sources like moringa, Bambara groundnut, and termites are added to enhance the vitamins, minerals, proteins, and carbohydrates in the resulting beverages.[28,29,75]
Additionally, natural fermentation of sorghum for 48 hours at room temperature led to reductions in fat (2.5-16% reduction), fiber (20.8-40.4% reduction), carbohydrates (0.32-1.4% reduction), and most minerals (0.02-7.2% reduction).[74] To counteract these losses, nutrients from sources like moringa, Bambara groundnut, and termites are added to enhance the vitamins, minerals, proteins, and carbohydrates in the resulting beverages.[28,29,75]

Non-alcoholic cereal beverages (NACBs) are commonly made through natural fermentation at home, involving a mix of microorganisms and yeast.[32] Natural fermentation is heavily influenced by raw materials and environmental factors, which ultimately determine the specific microorganisms responsible for creating the unique sensory characteristics of NACBs.[17] Conversely, natural fermentation can enhance nutrient bioavailability, with protein levels increasing from 19.22 to 22.46, ash from 3.82 to 4.16%, and fiber from 5.24 to 4.16% over 48 hours.[76] It also helps decrease anti-nutrients, such as phytic acid (from 283.46 to 142.24%), oxalic acid (from 5.86 to 1.28%), and tannins (from 8.85 to 3.89%) during the same period.[75] Although natural fermentation can improve the bioavailability of nutrients and reduce antinutrients, can lead to inconsistent quality and raise safety concerns due to potential bacterial contamination in naturally fermented foods.[22,75,77]

Due to concerns about harmful bacteria in traditional natural fermentation, conventional heating methods such as pasteurization and sterilization that utilize at least 85 and 121 °C for 30 and 15 minutes, respectively, have been introduced to ensure the safety of NACBs.[78] However, this has led to the potential loss of probiotic microorganisms, color and nutrients in NACBs, prompting researchers to explore alternative processing techniques. Emerging non-thermal processing methods such as Ultrasonic Treatment (UT), Pulsed Electric Field (PEF), and High-Hydrostatic Processing (HHP) are gaining traction because they operate at temperatures below 40 °C, thereby preserving sensitive nutrients and probiotics.[70,79] A comparison of processing methods for NACBs is presented in Table 2, detailing their temperature ranges, processing times, energy requirements, and key outcomes.

Although these techniques are not widely adopted in SSA yet, they present environmentally friendly and safe alternatives to conventional thermal methods, maintaining the nutritional quality and flavor of NACBs. Microwave Treatment carried out at temperatures between 70 and 90 °C, not only deactivates unwanted microorganisms but also significantly boosts beverage protein content.[79] Ultrasonic Treatment, which operates at a frequency of 20 kHz, promotes microbial growth and reduces fermentation times, enhancing the profiles of phenolics and flavonoids while lowering sugar levels.[79] Pasteurization remains a critical process for ensuring the safety of NACBs, typically involving heating to about 55 °C for 15 minutes to eliminate bacteria and extend shelf life.[53] High-Hydrostatic Processing, which operates at around 400 MPa and 40 °C for five minutes, effectively reduces microbial levels while preserving key nutrients. [20,79] Overall, some innovative techniques signify a movement towards safer and more nutritious beverage production.

After the harmful bacteria in the beverages are eliminated using a non-thermal method, the fermentation process can be managed by utilizing enzymes and starter cultures to improve the nutritional and sensory characteristics of NACBs. The controlled fermentation with designated starter cultures has helped improve the consistency and overall quality of these beverages. Researchers have employed bacterial strains isolated from traditional fermentation to create NACBs, demonstrating the benefits of using starter cultures for safety and taste enhancement. Starter cultures have significantly modified the sensory characteristics of NACBs positively and negatively, leading to a demand for cultures that can replicate traditional flavors. Among the tested strains, *Lactobacillus brevis* was the most favored for pearl millet beverages, exhibiting enhanced sensory attributes such as color, aroma, and taste compared to unfermented versions,[81] while other strains like *Leuconostoc mesenteroides* and *Pediococcus pentosaceu*s showed potential but required further taste improvement.[53]

Table 2: Comparison of processing methods for non-alcoholic beverages: temperature ranges, processing times, energy requirements, and outcomes

Processing Method	Temperature Range	Processing Time	Energy Requirements	Results	References
Milling	-	Varies (depends on grain)	Moderate (depends on equipment)	Produces fine flour, increases surface area for enzymes	80
Soaking (Conditioning)	Room Temperature - 55 °C	Varies (1-24 hours)	Low	Softens endosperm and hardens bran for better milling	23
Enzymatic Hydrolysis	55 °C	2 hours	Moderate (depends on enzyme type)	Hydrolyzes starch into fermentable sugars, improves nutrition	60
Fermentation	20-37 °C	12-72 hours	Low	Enhances nutrient profiles, increases digestibility	31,53
Ultrasonic Treatment	20 kHz/130 W or 20 kHz/300 W	8 or 5 minutes	High	Increases phenolic, flavonoid content and antioxidant content, reduce fermentation time and sugar content.	70,79
Microwave Treatment	70-90 °C	Short bursts (minutes)	High (540-810 kW)	Increases protein content	79
Pulsed Electric Fields	35 kV/cm	Microseconds to seconds	High	Enhances isoflavone content, improves stability	20,79
High Hydrostatic Pressure	40-75 °C, 200-400 Mpa	5 minutes	High	Reduces microbial count, retains nutrients	20,79
Pasteurization	75 or 85 °C	30 or 15 minutes	Moderate to high	Destroys of good and harmful bacteria, extends shelf life	24
UV Treatment	4-30 °C, 253.7 nm	0-48 minutes	Moderate	Inactivates peroxidase activity, reduces the microbial count	79

After the harmful bacteria in the beverages are eliminated using a non-thermal method, the fermentation process can be managed by utilizing enzymes and starter cultures to improve the nutritional and sensory characteristics of NACBs. The controlled fermentation with designated starter cultures has helped improve the consistency and overall quality of these beverages. Researchers have employed bacterial strains isolated from traditional fermentation to create NACBs, demonstrating the benefits of using starter cultures for safety and taste enhancement. Starter cultures have significantly modified the sensory characteristics of NACBs, leading to a demand for cultures that can replicate traditional flavors. Among the tested strains, *Lactobacillus brevis* was the most favored for pearl millet beverages, exhibiting enhanced sensory attributes such as color, aroma, and taste compared to unfermented versions.[81] In contrast, other strains like *Leuconostoc mesenteroides* and *Pediococcus pentosaceus* showed potential but required further taste improvement.[53]

Additionally, fermentation with *L. acidophilus* improved the acceptability of non-dairy probiotic beverages, indicating the need for alternative raw materials for supplementation.[82] Although unflavoured probiotic beverages from maize fermented with *L. paracasei* were met with neutral consumer responses, incorporating fruit pulps and flavorings is suggested to enhance palatability.[83] Traditional beverages like *Mahewu* demonstrated a refreshing sour taste that aligns with consumer preferences, highlighting the importance of integrating indigenous knowledge into modern practices while noting that reliance solely on such beverages could lead to micronutrient deficiencies if not balanced with fruits and vegetables.[25] In the selection of bacteria for starter cultures, emphasis is also placed on choosing strains that produce exopolysaccharides to enhance the texture, flow, and flavor of NACBs.[27]

Exopolysaccharides are classified into homopolysaccharides (such as starch and cellulose) and heteropolysaccharides (including xanthan gum, pectin, and galactomannans), which are biopolymers produced by microorganisms, including lactic acid bacteria, during their growth. Key exopolysaccharides producing lactic acid bacteria include *Lactobacillus, Lactococcus, Bifidobacterium, Leuconostoc, Pediococcus, Streptococcus, Enterococcus,* and *Weissella* species.[36,84] Exopolysaccharides are known for their antioxidant properties and ability to inhibit biofilm formation by *Escherichia coli* and *Staphylococcus aureus*. Research shows that exopolysaccharides from *Lactobacillus* can alleviate liver damage by modulating intestinal microbiota and enhancing the immune response species.[36,84] Additionally, exopolysaccharides from *Lactobacillus plantarum* and *Lactiplantibacillus plantarum* have demonstrated anti-diabetic properties by inhibiting α-glucosidase and α-amylase enzymes. Exopolysaccharides offers various health benefits, including antioxidant effects, cholesterol reduction, immune system support, anti-aging properties, intestinal microbiota modulation, and antitumor activities species.[36,84]

NACBs often have a cloudy, brown-reddish, white-creamy, or dirty-grey appearance due to the presence of cereal particles not well-liked by consumers.[32] This appearance has limited the popularity of NACBs among those who have not tried them before, as they are often compared unfavorably to clear imported or alcoholic drinks. Many consumers are reluctant to try NACBs due to their appearance, not just their taste.[49] A study involving primarily a young audience (71% female, 24% male, mostly black students under 29) revealed that a naturally fermented non-alcoholic pearl millet beverage was disliked mainly for its appearance and color when compared to a filtered beverage produced under controlled fermentation conditions.[53] This hesitation is also affected by the dominance of Western carbonated and flavored soft drinks among the youth, leading to a lack of familiarity with traditional drinks such as NACBs. It may be important to filter NACBs to improve their quality and appeal to broader consumers.[23,53]

Researchers have suggested new techniques from beer brewing to improve the consumer appeal of NACBs by adopting advanced filtration techniques and controlled fermentation through starter cultures.[23,78] Additionally, these beverages are often sold on streets in used soft drink bottles that may not be adequately cleaned, which can be a turn-off for consumers. Proper packaging could improve non-alcoholic cereal beverages' shelf-life and beverages and enhance their presentation and attractiveness to customers.

Nutritional and Health Benefits of Non-Alcoholic Cereal Beverages

In modern society, simply having a delicious taste of food and beverages is no longer sufficient to satisfy customers prioritizing their well-being.[32] The increasing focus on fitness, health, and wellness among consumers has sparked a demand for food and beverages that offer specific health benefits, commonly known as functional foods and beverages.[85] The market for functional beverages was anticipated to reach $208.13 billion by 2024, with a forecasted Compound Annual Growth Rate of 7.5% from 2022 to 2027.[20] The rise in popularity of functional beverages such as NACBs can be attributed to their rich content of vitamins, antioxidants, and minerals,[32,86] as well as the increasing number of individuals with lactose intolerance and cow milk allergies seeking alternative options. Additionally, incorporating NACBs into one's diet is becoming a lifestyle trend due to their potential health benefits. Furthermore, consuming NACBs regularly has been associated with reducing the risk of developing chronic conditions like obesity, type 2 diabetes, and heart disease.[66,85]

Figure 2 illustrates the numerous advantages of consuming non-alcoholic cereal beverages made from various cereal grains. Millet-based non-alcoholic beverages have been proven to lower cholesterol and blood pressure, decrease cancer risk, help individuals with diabetes, ease diarrhea, have anti-allergenic and antimicrobial properties, and support gut health.[23,32] Maize-based non-alcoholic beverages specifically target genitourinary pathogens, among others.[23,31,69] Composite NACBs made from a blend of maize, millet, rice, or sorghum offer a combination of benefits, including enhancing cholesterol levels, promoting gut health, and possessing antimicrobial properties health.[23,32] Overall, these non-alcoholic cereal beverages offer diverse nutritional and health benefits. However, some studies have shown that fermentation can decrease crude protein, fiber, and mineral (ash) levels in certain beverages.[74] Consequently, relying on these beverages, such as *Mahewu*, as a main food source without supplementation may result in micronutrient deficiencies.[25]

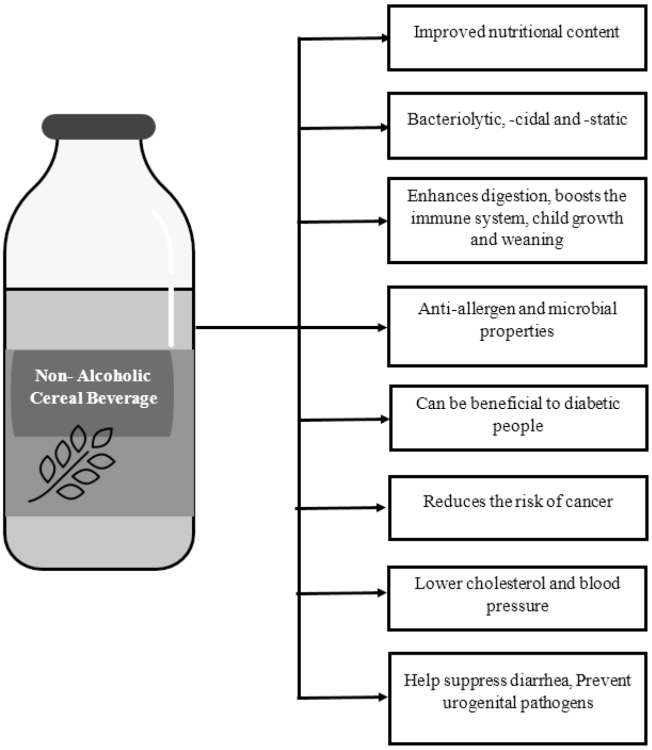

Fig. 2: Health benefits of non-alcoholic cereal beverages made from different grains. [23,31,69]

Insights, Challenges and Prospects of Non-Alcoholic Cereal Beverages

The addition of nutrients to NACBs through supplementation and fortification has shown promising results in addressing nutritional deficiencies (Table 1). The fortification and supplementation of NACBs have been shown to improve the nutritional and health properties of these beverages, potentially leading to economic advantages. Food fortification and supplementation are implemented through common staple foods, making them accessible to the broader population, including low-income individuals in rural and urban areas.[87] This approach is sustainable as it does not depend on external funding or distant markets; instead, it utilizes existing food production systems, which helps reduce costs.[87] The expense of fortifying a single food item is significantly lower than the costs of treating potential micronutrient deficiencies, which may require medication or even hospitalization.[15]

In addition to the health advantages of fortified foods, they contribute to the well-being of individuals, enhancing their productivity. It is important to recognize that undernutrition negatively impacts productivity, diminishing economic potential and exacerbating food insecurity.[88] By tackling nutritional deficiencies with fortified foods, we can enhance health outcomes and elevate overall productivity, promoting economic growth.

Increasing the levels of iron, protein, minerals, amino acids, vitamin C, and antioxidants, NACBs can help communities lacking access to essential nutrients. The fortification of NACBs offers various benefits, such as boosting immune function with vitamin C and reducing the risk of anemia with iron.[68,89] The bioavailability of nutrients in fermented cereal beverages is enhanced through fermentation, which disrupts the cereal cell wall, releasing enzymes and bioactive compounds. Additionally, the acidic environment created during fermentation boosts the absorption of certain nutrients while decreasing the levels of anti-nutrients such as hydrogen cyanide (by 52.3%), cyanogenic glycosides (by 66%), tannins (by 30%), and phytates (by 19–69%), which typically hinder nutrient availability.[74] This process significantly improves the bioavailability of essential minerals like iron, calcium, zinc, phosphorus, magnesium, and sodium, primarily by reducing phytate levels.[74] For instance, fermentation of millet and cowpea increased iron content from 7.9 to 34.7 mg/100 g, while sorghum and cowpea fermentation led to increases in sodium (from 2 to 4 mg) and iron (from 6.1 to 14.2 mg/100 g).[90]

Additionally, the protein content of *Bushera* increased from 7.79 to 11.63%.[90] Additionally, the consumption of probiotic bacteria in these beverages has been linked to improved metabolism and gut health.[91] These beverages significantly promote overall health in SSA communities, where individuals of all ages consume them as a dietary staple. The intake of NACBs differs according to personal health requirements and the formulations of the products. Nevertheless, general recommendations indicate a daily consumption of around 500 mL of NACBs, equating to less than 14% of total energy intake from fluids daily, based on the serving size of commercial *Mageu* available in South Africa. Furthermore, NACBs can serve as a social tool, bringing people together and providing economic opportunities for women who produce and sell them to support their families.

Across SSA, communities use a range of indigenous crops such as moringa, termites, aloe, Bambara groundnut, and beetroots for fortification and supplementation of NACBs, each offering unique nutritional benefits.[28,38,39,41,44] The selection of these additives is influenced by their availability and the specific dietary needs of the community. These fortificants and supplements can be incorporated into processing raw materials, biofortification, or beverage production. A successful example of fortification is seen in the commercialized *Mageu* in South Africa, which has been fortified with moringa. Recent advancements in biotechnology have made significant strides in addressing vitamin and mineral deficiencies through the biofortification of various crops. In India, schoolchildren who consumed iron-biofortified pearl millet demonstrated an increase in light physical activity by an average of 22.3 minutes daily.[92] Additionally, in Rwanda, the introduction of iron-biofortified beans led to notable improvements in iron levels among university women, who saw an increase in hemoglobin (3.8 g/L), serum ferritin concentration (0.1 log µg/L), and body index (0.5 mg/kg) after 28 days of consumption.[93] For every gram of iron consumed from the beans over the 128-days study, there was a corresponding significant increase of 4.2 g/L in hemoglobin levels.[93] Furthermore, substantial evidence indicates that pro-vitamin A biofortified orange sweet potatoes and maize have helped reduce vitamin A deficiency in several developing countries in SSA, including Zambia, Malawi, Mozambique, Uganda, and South Africa.[94–96] This widespread adoption of biofortified crops represents a significant step forward in combating micronutrient deficiencies and promoting better health outcomes globally. These biofortified crops can produce staple NACBs to combat micronutrient deficiencies.

Developing and implementing agricultural strategies to combat "hidden hunger," such as through staple food biofortification, is more effective than relying on nutrient intake from donor-funded supplementation and fortification programs.[95,97] Supplementation and fortification programs, while beneficial, are heavily dependent on the external funder, the purchasing power of individuals, consistent access to markets, and the availability of proper healthcare.[95,96,98] Additionally, there is a need for heightened awareness about the long-term effects of these nutrient supplements, which cannot be assured annually. Agricultural solutions offer a sustainable, self-sufficient, and comprehensive approach to delivering essential nutrients to communities through biofortified crops and related food products such as NACBs, minimizing the uncertainties linked to supplementation programs.[96,97]

Even with the exciting progress in NACBs development, there are still obstacles to overcome, such as the proper distribution of fortificants and supplements that can impact the taste and appearance of the beverages. For example, adding water-soluble iron salts to food can affect its sensory characteristics.[89] When interacting with phenolic compounds, these salts can lead to a blue or brown color and may impart a metallic flavor to liquid products.[99] When ferrous sulfate is incorporated into cereal flours in hot and humid environments, it can exacerbate lipid rancidity.[99] Another example, *Mageu* with added moringa may have a greenish hue and grassy aroma that could deter certain consumers.[53] These challenges may result in decreased consumer acceptance, as some may prefer the traditional versions of NACBs.

Future research studies may explore additional fortifying agents and supplements, particularly those derived from natural sources. The incorporation techniques of fortificants and supplements and their effects on nutritional content and health advantages could be assessed, along with their sensory qualities. Finding novel methods to increase consumer acceptance of fortified or supplemented beverages will be essential for market viability. Furthermore, fresh, innovative approaches must be devised to modernize these beverages for a wider audience. The demand for continued research and advancement in this area is apparent; input could be immensely valuable in the summarised areas:

Flavor and Taste Enhancement

Although starter cultures have improved the sensory qualities of NACBs, there is still a need to develop cultures that can accurately replicate traditional NACBs flavors, as existing strains may not fully satisfy consumer taste preferences. Additionally, NACBs fermented with specific strains have received mixed reactions from consumers, suggesting that unflavoured varieties may lack appeal, highlighting the importance of adding flavorings to enhance their taste. For example, strains such as *Leuconostoc mesenteroides* and *Pediococcus pentosaceus* have shown promise , but the beverages' flavors still need to be enhanced to boost consumer acceptance.[53] Therefore, further investigation into starter cultures and the supplementation of these beverages is essential for improving their sensory profiles and nutritional and health benefits.

Nutritional Deficiencies

Consistently consuming NACBs such as *Mahewu* without adequate supplementation with legumes, herbs, spices, cereals, fruits, or vegetables can result in micronutrient deficiencies.[25] The cereals commonly used in NACBs typically contain lower protein levels and essential amino acids. While fermentation can improve the nutrient profile in small amounts, it may not fulfill the daily nutritional needs typically met by dairy, necessitating the inclusion of other crops. These supplements can also offer additional health benefits; for instance, moringa, often called the miracle tree, can increase the protein content of such beverages. Fruits contribute fiber, vitamins, and potassium and can also enhance the flavor of NACBs. Furthermore, examining the nutritional advantages of fortified or supplemented beverages is important to understand their benefits better.

Microbial Research

NACBs face significant challenges, especially in microbial research and fermentation methods. There is a lack of comprehensive studies on the microbial factors affecting NACBs, especially regarding using single cultures in fermentation, which hampers the optimization of production processes. Conversely, various bacterial strains and yeasts have been identified from spontaneous fermentation methods in SSA. Still, most research has concentrated on dominant strains, overlooking lesser-known organisms that could impact the sensory characteristics of the final products. This gap highlights the importance of investigating the roles of these non-dominant bacteria and yeasts in improving flavor and quality.

Fermentation Techniques

Besides developing starter cultures, it is vital to standardize fermentation processes under controlled environments to ensure consistent and high-quality products. Such standardization would help reconcile traditional methods with industrial needs, preserving the unique flavors and nutritional advantages of NACBs while adhering to modern production standards. Furthermore, there is a need for innovative techniques to align the flavors of new beverages with those produced through traditional spontaneous fermentation. Addressing these issues is essential for promoting the industrialization of non-alcoholic cereal beverages in Africa, thereby improving their market presence and consumer acceptance.

Challenges in Industrial Applications

The industrialization of NACBs in SSA faces multiple interconnected challenges that affect their quality and market acceptance. Efforts to industrialize maize-based beverages, including fortification with herbs like moringa and starter cultures with thermophilic *Lactobacillus*, have encountered issues, as large-scale production can alter the unique flavors of these traditional beverages.[31]

Regulatory challenges also affect small-scale producers at the industrial level, especially since many traditional products were made under unsanitary conditions, raising quality and safety concerns. To tackle these issues, it is vital to implement measures such as Standard Operating Procedures (SOP), Prerequisite Programs (PRP), and Hazard Analysis Critical Control Point (HACCP) systems. Moreover, the increasing popularity of Western carbonated soft drinks poses a significant threat, particularly among younger consumers who may not be familiar with NACBs. This competition highlights the urgent need for consumer education to promote the nutritional advantages and health benefits of NACBs

Additionally, there is a need to investigate processing techniques that can extend shelf life and enhance flavor, such as high-hydrostatic processing, and ohmic heating. Lastly, validating packaging materials is crucial, particularly the need for transparent packaging, as many beverages are currently sold in opaque containers that may conceal product quality from consumers. A comprehensive approach to address these challenges is essential for the successful industrialization of NACBs in SSA.

Conclusion

The fortification and enhancement of NACBs in Africa offer a valuable opportunity to tackle widespread micronutrient deficiencies that pose major global health issues. Micronutrient deficiencies are responsible for 7.3% of worldwide deaths, particularly from iron and vitamin A deficiencies, highlighting the urgent need to improve the nutritional quality of these beverages. SSA alone accounts for 80% of global cases of zinc, iron, and vitamin A deficiencies. By incorporating nutrient-rich crops such as beetroots, winged termites, tigernut, and moringa, NACBs can become vital sources of essential nutrients for the population.

Despite the traditional production methods passed down through generations, there is a pressing need to modernize these processes. Evaluating and refining production conditions, such as fermentation duration and using traditional utensils, can help replicate the sensory qualities of these beverages on an industrial scale. Furthermore, understanding the microbial diversity involved in fermentation is crucial for developing starter cultures that consistently produce flavors like those of traditionally fermented beverages.

The current shelf life of less than five days due to uncontrolled fermentation presents another hurdle that must be addressed through modern preservation, packaging and storage techniques. Methods such as high-hydrostatic processing, sterile production environments and fortification can extend shelf life while preserving the functional benefits of probiotics and thermal-sensitive nutrients. Effective packaging and storage strategies are crucial for prolonging the shelf life of non-alcoholic beverages by preventing excessive fermentation and maintaining quality. As the market for functional beverages is projected to grow annually by 7.5% until

2027, NACBs can play a pivotal role in improving public health and economic stability in Africa.

However, these beverages must compete with well-marketed carbonated drinks, requiring strategic marketing and consumer education to highlight their health advantages. To ensure their acceptance and market success, further research is necessary on microbial diversity, effective starter culture development, standard processing methods, packaging and innovative fortification techniques. Addressing the challenges associated with the industrialization of non-alcoholic cereal beverages in Africa holds promise for enhancing nutritional intake and contributes significantly to public health initiatives. By leveraging traditional knowledge while embracing modern techniques, NACBs can emerge as key players in combating malnutrition and fostering economic growth.

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Informed Consent Statement

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This research does not involve any clinical trials.

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Author Contributions

- **Mmaphuti Abashone Ratau:** Conceptualization, Methodology, Formal analysis, visualisation and validation, writing - original draft preparation, writing - review and editing.
- **Oluwaseun Peter Bamidele:** Conceptualization, methodology, visualisation and validation, resources, supervision, writing - review and editing.
- **Victoria Adaora Jideani:** Conceptualization, visualisation and validation, resources, supervision, writing - review and editing.
- **Shonisani Eugenia Ramashia:** Conceptualization, visualisation and validation, resources, supervision, writing - review and editing.

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