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Review

Application and Acceptability of Microbiomes in the Production Process of Nigerian Indigenous Foods: Drive towards Responsible Production and Consumption

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ABSTRACT: In Nigeria, the use of microorganisms for food product modulation, development, and commercialization through biotechnological innovations remains unexplored and unaccepted. The microbiome-based sustainable innovation in the production process of Nigerian indigenous food requires a vigorous drive toward responsible consumption and production. The production process of locally fermented beverages and foods culturally varies in terms of fermentation techniques and is characterized by the distinctiveness of the microbiomes used for food and beverage production. This review was conducted to present the use of microbiome, its benefits, and utility as well as the perspectives toward and mediatory roles of biotechnology on the processing of locally fermented foods and their production in Nigeria. With the current concerns on global food insecurity, the utilization of modern molecular and genetic sciences to improve various rural food processing technologies to acceptable foreign exchange and socioeconomic scales has been gaining attention. Thus, further research on the various types of processing techniques for locally fermented foods using microbiomes in Nigeria is needed, with a focus on yield optimization using advanced techniques. This study demonstrates the adaptability of processed foods locally produced in Nigeria for the beneficial control of microbial dynamics, optimal nutrition, therapeutic, and organoleptic characteristics.

Keywords: agriculture, biotechnology, fermented foods, food-processing industry, microbiome

INTRODUCTION

Microbes, especially bacteria, have been used in industries to produce various products, including foods and feeds. Using innovative genetic technology, several microbes have been genetically manipulated for their relevant capability and potential to address global sustainable development goals, particularly in ensuring food security and overcoming health challenges (Akinsemolu, 2018). In Africa, microbes have been used in food processing for a thousand years, whether naturally or artificially, and beneficial knowledge about these microbes has been passed down from generation to generation. Most Nigerian and West African staple, ceremonial, and traditional diets from time immemorial are processed using crude fermentation techniques (Mokoena et al., 2016). In recent decades, these African foods have been found to have probiotics and a spectrum of bacterial fermenters essential for good health (Capozzi et al., 2020). The sources of several spontaneous microbes responsible for fermentation are not fully understood, and probiotic activities in many indigenous locally processed foods are

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diverse. Capozzi et al. (2017) stated that microbes and several of the raw materials used by ancient locals for food processing have multidimensional relationships.

The nature of the trade-off between the partnering microbes and their substrate characteristics determines the kinetic trajectory of microbial metabolic activities and bioactivities (Rezac et al., 2018). Thus, the release of bioactive compounds in the form of metabolism by-products could alter the traditional, economic, industrial, health, and domestic values of the end products or compromise their organoleptic quality. Many African communities and households have perfected the use of ancient fermentation technologies long before the discovery of starter culture application. The steeping and later processing phases of fermented food products primarily rely on the spontaneous action of preexisting microbes (Fischer and Van Loo, 2021). Over the years, the wide range of foods and beverages has been recognized as an indigenous cultural marker of ethnicity and beliefs. The introduction of new techniques for indigenous food production has improved the quality and helped control microbial activities for the desired flavor, taste, and texture of the resulting product (Teniola et al., 2005). The indigenous knowledge about the roles and application of different microbes in the Nigerian food processing system needs to be adequately reported. The lack of access to relevant information has affected the orientation and perception of Africans toward fermented diet. Some advances in food industry have been made, such as the use of *Levilactobacillus brevis* as starter culture in combination with *Saccharomyces cerevisiae* for the production of *ogi* (a locally fermented cereal paste made from maize or sorghum/millet in Nigeria) to improve its taste (Aworh, 2015). Likewise, the use of the combination of *Streptococcus lactis*, *Lactiplantibacillus plantarum*, and *Saccharomyces rouxii* as starter culture for the production of dry *ogi* powder reportedly improved the acceptability of this product (Olaniran et al., 2019). This study aimed to improve the existing knowledge of and perception toward the application of microbes in the production process of healthy foods in Nigeria.

BIOTECHNOLOGY AND PRO-TECHNOLOGY IN FOOD PRODUCTION

Microorganisms play an important role in food production, and they can negatively or positively impact their valued applications and also influence human's perception toward the derived products (Kavitake et al., 2018). The rapid development of the food processing sector of many African economies in recent decades has been driven by biotechnology, affording process control capacity. Furthermore, it has relatively influenced the global food basket with the emergence of genetically modified, organic, and inorganic foods. Since the last few decades, biotechnological applications have been fundamentally accepted and become attractive, versatile, and amenable to addressing concerns about global food insecurity (Kumar and Dubey, 2016).

Issues regarding food preservation, safety, nutrient quality, value depreciation, and loss due to diseases have been addressed using biological agents or their products as well as biogenetic engineering, which are concepts of biotechnology. Consequently, the introduction of new strains of microorganisms prevent harmful health implications, facilitate digestion, stimulate the absorption of beneficial biochemical, improve activities of enzymes, and hormones at different stages of food processing (farm-to-fork) to processed food contents (Adekoya et al., 2019). This is biotechnologically achieved through a metabolic process control or a genetic manipulation to optimize the yield and diversity of quality by-products. Furthermore, the biotechnology equally allows chemical reconfiguration of hitherto toxic metabolites into beneficially safe compounds in food. Similarly, microorganisms may act as vehicles for beneficial gene transfers and mutagens in crop breeding or genetic re-engineering processes (genetic modification of organic crops). The application of biotechnological methods is important for fermentation and the production of microbiomes in commercial quantity. It is also crucial to the improvement of the socioeconomic status of the people in any country, especially the developing ones. These biotechnological methods have been used in the manufacture of ethanol, acetone, organic acid, enzyme (from biological agents), riboflavin, and other vitamins used for pharmaceuticals and as dietary supplements (Teitelbaum and Walker, 2002).

Teitelbaum and Walker (2002) reported that naturally occurring bacteria or their mutants are applied in foods, beverages, and animal feeds as fermenters and probiotics. This improves the digestive, mental, and cardiac health of both humans and animals. While probiotics are attracting the attention of many African nations owing to their application in food processing and production of local dietary supplements, they have been proven by medical research to mediate allergies, colitis, Crohn's disease, cancer, infections (diarrhea, gastroenteritis, urinary tract infection, and dermatomycosis), and ulcer (Terpou et al., 2019). Fermented foods are a major source of probiotics among Nigerians. The increasing application of probiotics, whether in great or less amount, and their corresponding action(s) in foods and animal feeds are recent concepts perceived by some schools to be free of repercussion(s). This was hypothetically derived from the counteractive effect or promoting influence of probiotics on gut microbes (Zdolec et al., 2018). In this context, pro-technology refers to ancient food processing meth-

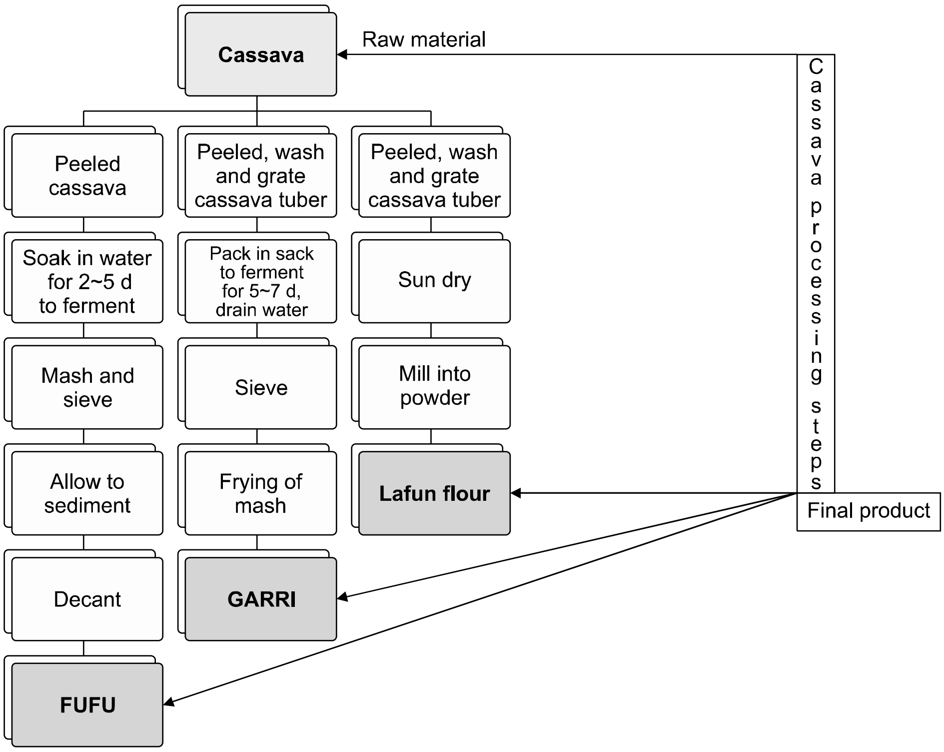

Fig. 1. Schematic representation of processes involved in the production of *fufu*, *garri*, and *lafun* from cassava. Data from the article of Oyeyinka et al. (2019).

ods common to many African people, whose knowledge and skills have been passed down from generation to generation (Adeyeye, 2017). Such methods are also popularly known to be pro-biotechnological, especially fermentation (Fig. 1∼4), and used by locals for the domestic processing and preservation of foods for household consumption or income generation. The methods described in the Fig. 1∼4 for production are simple, cost effective, require simple equipment, no special starter culture, no chemical added are still practice in many Nigerian suburban households, cultures, and ethnic affiliations (Adepoju et al., 2016; Olasupo et al., 2016; Adesulu-Dahunsi et al., 2017; Oyeyinka et al., 2019; Olaniran et al., 2020a, 2020b).

BENEFITS AND SIGNIFICANCE OF FERMENTED FOOD PRODUCTS

In Nigeria, for example, the processing of local beverages, staples, spices, and foods that involves macerating, soaking, draining, and fermentation is driven by the activities of bacteria and fungi. Microorganisms have already been used in many African food cultures as natural sources of probiotics and vitamins long before their scientific validation (Adeyeye, 2017; Bolaji et al., 2017). Cassava, cereals (millet, maize, sorghums, and rice), fruits, vegetables, and animal products are some of the renewable raw materials for processing locally fermented functional foods, spices, beverages, and dietary staples in different parts of Nigeria. Aside from containing beneficial microorganisms

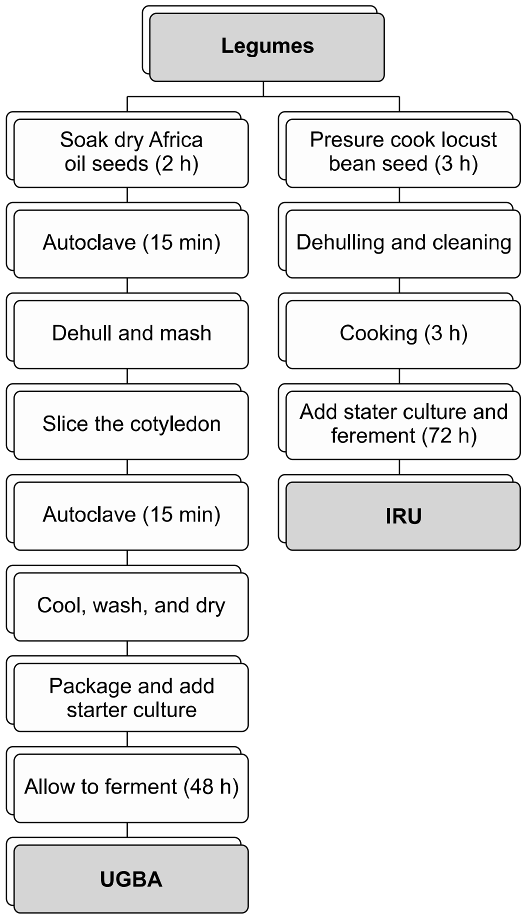

Fig. 2. Processing of fermented food from legumes (*Iru* and Ugba) using starter culture. Data from the article of Olasupo et al. (2016) and Olaniran et al. (2020c).

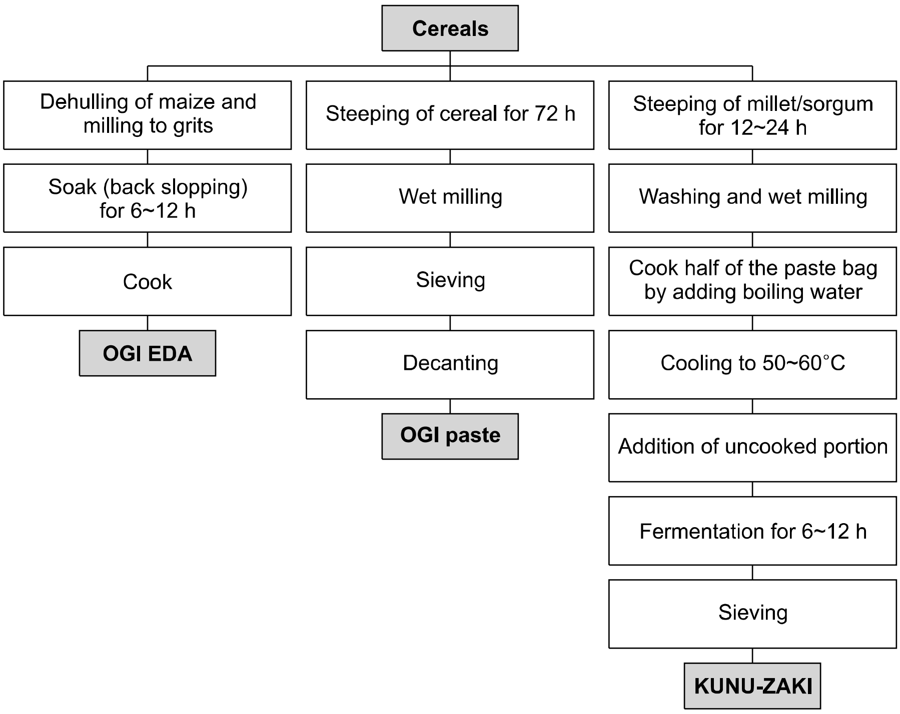

Fig. 3. Production flowchart selected fermented product (*ogi*-eda, *ogi* paste, and *kunu-zaki*) from cereals. Data from the article of Adepoju et al. (2016), Adesulu-Dahunsi et al. (2017), and Olaniran et al. (2020b).

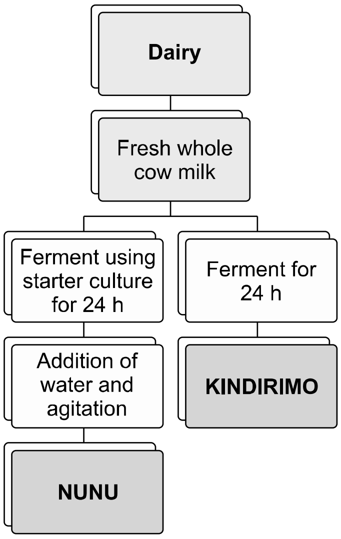

Fig. 4. Production method for *nunu* and kindirimo from dairy. Data from the article of Adepoju et al. (2016).

capable of breaking down anti-nutritional food components, these food products are in their various trial stages for the preparation of weaning foods or supplements for infants (Kavitake et al., 2018). Malnutrition in children is a concern in Africa. The inaccessibility of many growing children to protein-rich or balanced diets impelled the screening of locally fermented foods as an affordable, natural, or organic substitute, or supplement to synthetic brands of weaning foods. It has been reported that a minimum of 10^8 bacteria per 1 mL must reach the colon alive to attain significant health beneficial effect such as immune-modulatory, anti-colon cancer, anticholesterolemic, maintenance of gut pH, absorption of calcium and phosphorous in the intestine (Sanders et al., 2018).

Elie Metchnikoff, a Nobel laureate, was the first microbiologist to report that the consumption of sour milk containing *Lactobacillus delbrueckii* subsp. *bulgaricus* was responsible for the longevity of Bulgarian peasants at the beginning of the 20th century (Underhill et al., 2016). Salminen et al. (1998) also attributed such an effect to the presence of probiotics or microbial cells or their components or products in foods. As defined by the FAO and WHO (2002), probiotics are live microorganisms that exert a beneficial physiological effect on the host when administered in an adequate amount. The spectrum of fermented foods in Nigeria, although understudied, may be rich in probiotics that are yet to be elucidated. A variety of microorganisms reported in the literature to have potential probiotic effects primarily belong to the *Lactobacillus* and *Bifidobacterium* genera (Clark et al., 1993; Taha et al., 2017; Olaniran et al., 2020b). Bacterial species such as *Acetobacter aceti*, *Acetobacter cerevisiae*, *Acetobacter fabarum*, *Acetobacter lovaniensis*, *Acetobacter malorum*, *Acetobacter orientalis*, *Acetobacter pasteurianus*, *Acetobacter tropicalis*, *Arthrobacter nicotianae*, *Arthrobacter variabilis*, *Leuconostoc mesenteroides*, *L. plantarum*, *Lactobacillus amylovorus*, *Lactobacillus delbrueckii*, *L. brevis*, *Limosilactobacillus fermentum*, *Pediococcus pentosaceus*, and *Pediococcus acidilactici* are implicated in many fermented foods in Nigeria, such as *ogi*, *agadagidi* (ripe plantain pulp), *dawadawa* (African locust bean), *eketeke* (from fermented oil palm nut), *ugba* (African oil bean), *ukwa* (African breadfruit), palm wine, *burukutu*, *wara*, etc. (Sanni et al., 2002; Olasupo et al., 2016).

Unlike biotechnology, pro-technology is usually a non-standardized process that does not pay much attention to hygiene control, quality control (QC), and health safety, which are basic needs for a safe consumption. This may be the reason why many locally processed foods in Nigeria are not accepted for consumption by the elite or urban dwellers. Foods and beverages derived from pro-technology are assumed to predispose consumers to diarrhea, food poisoning, and morbidity (Møretrø and Langsrud, 2017).

QUALITY ASSURANCE (QA) OF FOOD PRODUCTS

It is difficult to discuss modern biotechnology for handling bacteria in food production without recourse to QA and QC processes. QC is a reactive system that focuses on legal requirements and emphasizes statistically relevant measurement performances, whereas QA is concerned with preventive approaches that emphasize operational procedures. Food microbiologists use two approaches to establish QA and QC parameters: first is to determine the total load of microbes in a sample, and second is to determine the presence or absence of a particular microbial species, usually a pathogen, or a related type used as an indicator. Thus, while the QA test aims to ensure that the food products meet statutory requirements, the QC test is focused on public health impacts, with regulatory requirements as an integral part of the testing procedure (Paiva, 2013). Aside from the general testing requirements under QC programs, there has been an added element of QA that is vigorously pursued under the implementation of quality management systems, such as Hazard Analysis & Critical Control Points. To further improve the utility of these processes, rapid microbiological detection techniques that are more reliable, sensitive, and accurate need to be developed (Knaflewska and Pospiech, 2007) compared with conventional method. Accordingly, much effort has been devoted to the reduction of assay time and replacement of visible endpoints with other alternative measurements.

Several biotechniques are currently available for ensuring the safety of foods and food derivatives. These include the electrical method, which is based on the principle of impedance or conductance; chemical methods, e.g., direct epifluorescent filter technique, bacterial adenosine triphosphate bioluminescence, flow cytometry, biosensors, agglutination, or immunological assays; and nucleic acid technologies, which include polymerase chain reaction, ribotyping, and microarrays (Saravanan et al., 2021).

GENETIC ENGINEERING: INOCULUM AND STRAIN DEVELOPMENT

Genetic engineering, which is also referred to as recombinant DNA technology, is a process that involves genetic manipulation to obtain specific trait(s) expression or selective attributes. In this process, segment of DNA (genes) are introduced into a host using a variety of techniques that involves the use of a vector. The foreign DNA is then incorporated into the host and is replicated and passed on to the progeny daughter cells along with the rest of the DNA. This technique transforms bacterial cells and causes them to acquire attributes that are valuable in the production of commercially important products. One example is the production of human insulin (used for diabetes treatment) and growth hormone (somatotropin used for pituitary dwarfism treatment). The technique is also very useful for strain development. When microorganisms are introduced into adaptive mode, they produce mutagens with beneficial potential that can be used in food preservation and processing (Collins-Thompson et al., 1991).

The development of microorganisms from a dormant stock culture or natural source to an optimal state viable for use in substrate treatment or as a fermenter is called inoculum development. Strain development involves the use of genetic engineering for developing strain(s) useful in fermentation or food production processes. The resultant organism is called recombinant organism (strain) because its genetic make-up has been altered through recombinant and the rDNA technology (Deckers et al., 2020). Starter cultures, which largely comprise lactic acid bacteria (LAB), are food-grade microorganisms commonly used to produce fermented foods with desirable appearance, taste, texture, and flavor. Suffice to say, their inclusion helps facilitate the biochemical modulation of food during the fermentation process while also reducing the process timeline. This is one of the advantages of biotechnology over pro-technology, which relies more on the slow natural activities of spontaneous microorganisms rather than the use of starter culture to modify physical conditions and accelerate the turnover time. The types of fermented foods for which commercial starter cultures are currently used include dairy (cheese, sour cream, and yogurt), meat (sausages), and vegetable (pickles, sauerkraut, and olives) products. For starter cultures to be effective during food fermentation, they must carefully overwhelm the naturally occurring microflora and produce the desired end products of fermentation (Capozzi et al., 2020). Several activities essential for food fermentation, including lactose metabolism, proteinase activity, oligopeptide transport, bacteriophage resistance mechanisms, bacteriocin exudation, evolving immunity (bacteriocin resistance), exopolysaccharide production, and citrate utilization, are encoded on the plasmid of LAB. Recent advances in molecular technology have enabled the development of superior strains of starter cultures for industrial food applications. The improved features of these strains include bacteriophage resistance, genetic stability, reduced variation, and predictability in performance (Daly et al., 1996).

TRENDS IN THE APPLICATION OF MICROORGANISMS IN FOOD PRODUCTION PROCESSES

The importance of microorganisms in food production processes or value chain was first realized in 1837 when scientists discovered the application of yeast for alcohol production *via* fermentation. Furthermore, Louis Pasteur, a French chemist and biologist, equally reported the biological phenomena leading to the production of beer and vinegar in the 1860s. He attributed this to microorganism activities (Daly et al., 1996; Raman et al., 2014). However, it was not until after the Second World War that the industrial application of fermentation technology in food processing began to develop and evolve into the recent concept of biotechnology, which relied more on standardized but controlled processes for the production of a wide variety of acceptable foods. This inadvertently suggests that fermented foods are regular diets among populations of diverse cultures and traditions from antiquity until now.

Fermentation is one of the oldest food transformation and preservation techniques and is philosophically viewed from two perspectives, namely, pro-technology (before the emergence of modern biotechnology) and biotechnology. Fermentation facilitates not only the preservation of foods but also their biochemical modulation for enhanced health and nutritional benefits coupled with profound organoleptic quality improvement. This process affords spatial requirements conducive for the proliferation of useful beneficial microbes and the competitive exclusion of harmful species capable of causing spoilage coupled with value depreciation of the food (Olaniran et al., 2020a). Daly et al. (1996), Raman et al. (2014), and Olaniran et al. (2020b) reported that derivatives from the process in the form of organic substances facilitate food preservation and generation of distinctly novel products important for improving food quality and safety. Nature provides countless microorganisms capable of causing spontaneous fermentation of stored foods. This process has been applied by mankind for thousands of years and involves the use of yeasts, molds, and bacteria to make bread, beer, wine, vinegar, yogurt, and cheese. Furthermore, the involvement of the aforementioned organisms is fundamental in the production of fermented fish, meat, and vegetables as well as in food preservation. Bacteria, yeasts, and molds are the most commonly implicated microorganisms in food production since time immemorial and are used either individually or in combination for optimal results. They have been widely used as biological agents in the production of organic acids, alcohols, esters, and other viable economic products of organic origin (Olaniran et al., 2015). Similarly, the application of fermentation technology and microorganisms of diverse origins as fermenters has been experiencing innovations, expansion, and development since the last decade (Guerzoni, 2010). Recently, Ayanniran et al. (2020) isolated and identified six yeast genera (*Galactomyces*, *Candida*, *Saccharomyces*, *Cyberlindnera*, *Trichosporon*, and *Meyerozyma*) from fermented sorghum paste (*ogi-baba*), *fufu* (retted cassava), *burukutu* (traditional beer made from malted millet or milled corn), *agadagidi* (from fermented plantain), and palm wine using a combination of molecular and phenotypic tests.

Microorganisms and their natural fermentation capabilities are being investigated to improve our understanding of the dynamics of changeable competitive exclusion processes. These fermenters suppress poisonous, spoilage, and pathogenic species in bioreactive systems, as well as human and animal guts (Sanders et al., 2018). Emerging reports on the activities of these fermenters and other probiotic species confirmed their ability to subvert the pathogenesis of food microbiomes. Food contamination during storage and their resultant bioactivities as well as health implications are becoming concerns to the global food safety drive. It is noteworthy that the capacity of pathogenic bacteria and fungi to render foods unfit for consumption is facilitated by a combination of intrinsic and extrinsic factors (Rawat, 2015; Olaniran and Abiose, 2018). The use of raw foods, vegetables, poorly cooked animal proteins, and other ingredients from unsafe sources, poor cooking (heat processing), and improper handling, storage, and preservation of food increase human susceptibility to foodborne diseases. Furthermore, exposure of ready-to-eat food for several hours between preparation and consumption; poor reheating, even if originally frozen; and poor hygienic disposition induce cross-contamination (FAO and WHO, 2019). This may cause public health issues and foster food-related infections. The process of food deterioration involves both ecological and biological phenomena caused by a range of microbial activities that are mainly biochemical, such as oxidation, enzymatic-browning, nonenzymatic browning, growth, moisture control, and metabolism. Under favorable conditions, these activities facilitate the oxidative reactions and exudation of toxic chemicals that eventually compromise the taste, smell, and color of food (Hernández-Cortez et al., 2017). Consequently, the composition, and diversity of food microbial contaminants, either from soil residue, or long-term association, can provide good biological tips on potential fermentation cultures, probiotics, and spoilage species (WHO, 2005; USDA, 2012). At this point, it is logical to associate the aforementioned attributes to pro-techniques, which over time evolved into the more recent standardized methods modified for industrial purposes.

FIBER RETTING

Retting is the process by which the pectic material that binds fibers to the flax stem is broken down by microbiomes (Rasmina et al., 2011). In Nigeria, the indigenous foods produced through retting, such as *fufu* and *garri*, are major fermented food from cassava. *Bacillus* sp. plays a major role in the retting of cassava in the production of *fufu* (Oyeyinka et al., 2019). The acceptable qualities of cooked *fufu* are its smoothness and fluffiness, which make it easy to swallow. Such qualities are caused by the biophysical composition of the fresh cassava root, mainly fiber, and the level of effectiveness of retting followed by sieving during the production. Retting enhances the disintegration of insoluble fibers, cellulolytic and pectinolytic enzymes. The distinct sour taste, flavor, appearance, and texture of *fufu* due to the microbiomes are primarily recognized as features for consumer's acceptance and quality (Sobowale et al., 2007; Olaniran and Abiose, 2018). *Corynebacterium manihot*, *Geotrichum candidum*, *Lactobacillus* sp., *Leuconostoc* sp., and *Candida* sp. are reportedly important in retting during the production of organic acids from starch and the breakdown of linamarin. They were also implicated in the production of ketones and aldehydes, which are important for the valorization of the flavor of *garri* flakes and in the removal of cyanide from the mash (Chijioke et al., 2021). *Lafun* is another cassava derivative that is a popular fermented food in West Africa produced through retting. *Lactobacillus* sp., *Leuconostoc* sp., *Streptococcus* sp., *Geotrichum candidum*, *Corynebacterium* sp., and *Candida tropicalis* have been used in the processing of cassava root tubers into *fufu* and *lafun* powders. Sobowale et al. (2007) produced *fufu* by incorporating *L. plantarum* starter culture without any significant effect on the pasting property and odor. The use of starter cultures is preferred for the active/speedy acidification of finished products as it lowers the pH to a definite point and inhibits the development of undesirable/unpalatable bacteria. Furthermore, starter cultures have been used in the commercial production of *fufu* and by many other food industries in the country (Flibert et al., 2016).

MICROBIOME APPLICATION IN NIGERIAN INDIGENOUS FOOD PRODUCTION PROCESSES

Food production is one of the oldest occupations ever undertaken by humans and has been a part of indigenous knowledge for a thousand years (Clark et al., 1993). Knowledge of indigenous food defines human food production, distribution, and consumption heritage. It also shapes the diverse cultural methods employed for the recycling of their by-products. Furthermore, such a millennial relationship with indigenous foods has driven the natural selection of foods as ethnic markers, synonymous with the identity, and culture of a particular ethnic group in the African continent. Over the years, people have learned to prepare, eat, and conserve their traditional foods along with a particular cultural orientation. Suffice to say, the food production methods, types, and eating habits within many indigenous communities characterize their culture, uphold their traditions, and strengthen their cultural knowledge and bonds in the world (Bolaji et al., 2017). An exponentially growing population in the country meeting food demands by diversifying methods used for food production is becoming exigent and urgent. Furthermore, it gives impetus to the corresponding effort at cutting back on crop losses and wastages due to diseases and poor storage challenges, respectively (Olaniran et al., 2020c). The rates of adoption of technology and research results in Nigeria and Africa have also had a revolutionizing effect on food production in the country. Also, different government policies, and approaches, such as the millennium, and sustainable development goals, have significantly affected the level of food production in Nigeria over the decades (Bolaji et al., 2017). While microorganisms such as bacteria, fungi, and yeasts are still spontaneously used in food processing, even to date, knowledge of their identity, benefits, and mode of actions remains incompletely understood (Raveendran et al., 2018).

More recent novel ways and technology are currently available for the purposeful application of bacteria or other microbes in food processing to improve their shelf-life, flavor, nutrition, digestibility, and safety characteristics (Olaniran and Abiose, 2019). Indigenous fermented foods form an integral part of the nation's cultural legacy since civilization. Such foods are accepted not only for their pleasant taste but also for their lasting storage that is afforded by the presence of high acid level (Fig. 1). This suggests that fermentation is a historical and important method for food preservation, particularly at a time when modern appliances, such as refrigerators, and freezers, were lacking (Olaniran et al., 2020a). Fermented foods provide sustainable health benefits to humans; hence, a considerable portion of most of the consumers' nutritional needs is met by fermented foods and beverages (Oghbaei and Prakash, 2016). In Nigeria, the classification of fermented foods can be based on raw/starting materials or substrates used in production. As presented in Table 1, cereals (*pito*, *ogi*, and *burukutu*), legumes (*ugba*, *ogiri*, *okpiye*, and *iru/dawadawa*), tubers (*fufu* and *lafun garri*), fruits/vegetables (*agadagidi* and *ukwa*), animal proteins (*wara* and *nono*), and beverage (palm wine) are classified as fermented products (Oguntoyinbo et al., 2016; Chukwu et al., 2018). Microorganisms found in foods are classified as bacteria, yeasts, and molds. While molds, which are mainly associated with food spoilage, have limited use in the food industry, yeasts are more attractive owing to their ability to ferment sugars and produce ethanol and carbon dioxide. Bacteria that are relevant in food production include LAB, propionic acid bacteria (PAB), and acetic acid bacteria (Food Microbiology Organizing Committee, 2017). They are also known for their efficient carbohydrate fermentation and substrate-level phosphorylation. *Lactobacillus*, *Pediococcus*, *Leuconostoc*, *Streptococcus*, *Lactococcus*, *Enterococcus*, *Oenococcus*, *Tetragenococcus*, *Carnobacterium*, *Vagococcus*, and *Weissella* are the common LAB implicated in the Nigerian food industries (Olaniran et al., 2020b). The bacteriocins produced by LAB have antimicrobial activities and antagonizes other bacteria that are less active or opportunistically harmful (Sanders et al., 2018). Unlike LAB, PAB are Gram-positive, nonspore-forming, nonmotile, rodlike, facultative anaerobes belonging to the family Propionibacteriaceae and the genus *Propionibacterium*. They are characterized by the formation of propionic acid as a consequence of propionic acid fermentation, dependent on coenzyme B12 and the presence of a high content of G+C (65～67%). Based on the peculiarities of their habitat, PAB are divided into lactic or classical and cutaneous strains. Lactic PAB are mostly isolated from milk, fermented dairy products, cheese, some species of vegetables, and fruits, whereas cutaneous PAB are mainly anaerobic microflora of healthy human and ruminant animals (Oluwatofunmi et al., 2015). Traditionally, PAB are known to convert lactic acid to propionic acid, acetic acid, and carbon dioxide; hence, they act as the control for undesirable microorganisms in food. Propionic acid and its salts are accepted preservatives for industrial use in bread-baking and silage production owing to their inhibitory activities against molds and *Bacillus* sp. (Paiva, 2013).

The current food processing methods are expanding to include either the back slopping method (direct addition of LAB) or the use of functional starter culture (Kavitake et al., 2018). Rodlike or coccus LAB are the major end products of homo- or hetero-fermentative metabolism that has been associated with the production of Nigerian indigenous fermented foods, such as *ogi*, *wara*, *kunu-zaki*, *burukutu*, *fura de nunu*, and *iru*. Several studies on LAB suggested that they play significant roles in human health and diets and are generally recognized as safe (Ibeabuchi et al., 2014; Adepoju et al., 2016; Ojewumi et al., 2016). Leguminous seeds of Bambara, yam bean, African oil bean, locust bean, soybean, and melon are rich in protein and used as supplementary raw materials for food production or as primary materials for the local production of different beverages (Ojewumi et al., 2016). African oil seeds are used under controlled fermentation for the production of *ugba* with a mixed culture of *Bacillus licheniformis* and *Bacillus subtilis* (Olasupo et al., 2016). *Dadawa* (*iru*) prepared from the seeds of African locust bean (*Parkia biglobosa*) can be used in much the same ways bouillon cubes are used in the Western world. The dominant genera of bacteria are *Bacillus* and *Staphylococcus* (Olaniran et al., 2020c). They serve as sources of high protein and have high potential for use as basic ingredients in food supplementation. *Okpiye* and *ogiri*, which are also fermented products similar to *iru*, are produced from the seeds of *Prosopis africana*, castor oil bean (*Ricinus communis*), and melon seeds (*Citrullus vulgaris*) (Table 1). Negligible application of major microbiomes associated with their fermentation of these foods are explored for the industrial production despite identification researches already carried out (Nwaiwu et al., 2016; Adekoya et al., 2017). Mixed starter cultures of *B. subtilis* are now used in the industrial production of *iru* (*dadawa*). The use of these bacteria cultures and seeds in food production helps augment protein in many fermented local dishes in addition to sufficing as nutritional substitutes for animal meat (Adesulu-Dahunsi, 2017). *B. subtilis* also plays a significant role in the fermentation process of various fruits and vegetables. It has been widely used for feed enhancements in several dairy and nondairy fermented foods and the improvement of the health and well-being of humans (Okoronkwo, 2014).

Cereals are most commonly fermented by four LAB genera, namely, *Lactobacillus* sp., *Lactococcus* sp., *Leuconostoc* sp., and *Pediococcus* sp. during the production of *ogi*. This product has been upgraded to the industrial scale using starter cultures. In a few studies, *Weissella* sp. was isolated as the predominant species in cereal fermentation (Agyei et al., 2020). In Nigeria, *L. plantarum* and *L. fermentum* strains are used in the production and processing of food from millet, sorghum, rice, and maize (Adekoya et al., 2019). Similar to all other local dishes, Nigerian sorghum can be classified into pastes, porridge, and beverages. This food product diversity suggests a different processing approach and more efficient use of raw materials. The application of fermentation can reduce the viscosity of cereal gruel and increase the level of energy in foods. Some of the local beverages, such as *burukutu* and *pito*, are mainly produced from the grains of sorghum; *kunu* is

Table 1. Beneficial microbes applied in the production of some fermented foods and beverages in Nigeria

Food/beverage	Product description	Beneficial microbes	References
Garri	Creamy white granular flour with a fermented or sour taste	*Corynebacterium*, *Lactis*, *Bacillus subtilis*, *Klebsiella* sp., *Candida tropicalis*, *Candida krusei*, *Lactiplantibacillus plantarum*, *Leuconostoc mesenteroides*, *Lactobacillus casei*, *Lactobacillus jensenii*, *Levilactobacillus brevis*, *Lactobacillus leichmannii*, *Lactobacillus delbrueckii*, *Scolecotrichum graminis*	Sobowale et al., 2007; Oyeyinka et al., 2019; Ayanniran et al., 2020
Fufu	Fermented white paste		
Lafun	Fibrous powdery cassava derivative		
Popo garri	Dry flakes with sour flavor eaten as a snack in the Mid-West of Nigeria		
Burukutu	Alcoholic beverage of vinegar-like flavor produced from Sorghum	*Acetobacter* sp., *Saccharomyces cereviseae*, *Candida* sp., *Streptococcus lactis*, *Limosilactobacillus fermentum*, *Enterobacter* sp., *Saccharomyces chavelieri*, *L. mesenteroides*	Alo et al., 2012; Okoronkwo, 2014; Adepoju et al., 2016
Kunun-zaki	Fermented beverage from millet	*Pediococcus pentosaceus*, *Enterococcus faecalis*, *Lactobacillus cellobiosus*, *Lactobacillus salivarius*, *Lactobacillus acidophilus*, *L. casei*, *L. jensenii*, *L. plantarum*, *Weissella confusa*, *L. fermentum*, *Lactococcus lactis*	Franz and Holzapfel, 2011; Adebayo and Ibraheem, 2015; Adepoju et al., 2016; Adebo, 2020
Kunun-gyada	Fermented cereal pudding made from millet or maize or both and groundnut		
Pito	Local beverage drink from either maize, sorghum, or their combination	*Geotrichum candidum*, *Lactobacillus* sp., *Candida* sp.	Achi and Ukwuru, 2015
Ogiri	Fermented melon seeds/castor oil seeds/ fluted pumpkin seeds	*B. subtilis*, *Pediococcus* sp., *Bacillus megateruim*, *Bacillus firmus*, *Proteus*, *Escherichia coli*, *Proteus*, *Pediococcus* sp., *Alcaligenes* sp., *Pseudomonas aeruginosa*, *Micrococcuss* sp., *Staphylococcus* sp.	Ibeabuchi et al., 2014; Chukwu et al., 2018
Ogi	Fermented slurry processed from maize or millet or sorghum or any of these combinations	*Saccharomyces cerevisiae*, *Lactobacillus* sp., *Fusarium* sp., *L. plantarum*, *L. leichmannii*, *L. casei*, *L. delbrueckii*, *L. jensenii*, *L. brevis*, *Candida mycoderma*, *Candida utilis*, *C. tropicalis*, *Rhodotorula glutinis*, *C. krusei*, *Lactobacillus* sp., *Fusarium* sp.	Teniola et al., 2005; Adesulu-Dahunsi et al., 2017; Adekoya et al., 2019; Olaniran et al., 2020a, 2020b
Ogi-eda	Red corn grits made from soaking in ogi water or water for spontaneous fermentation. Popular as a breakfast meal		
Masa/waina/ rice cake	Fermented puff batter of rice, millet, maize, or sorghum	Yeasts	Ayo et al., 2008; Evans et al., 2013; Malomo et al., 2019
Iru/dadawa	Fermented locust bean seeds used as food or condiment	*B. subtilis*, *B. megateruim*, *B. firmus*, *E. coli*, *Proteus*, *L. casei*, *L. plantarum*, *Bacillus licheniformis*, *Streptococcus* sp., *Rhizopus stolonifera*, *Aspergillus fumigatus*, *Triscelophorus monosporus*, *Pediococcus* sp., Coryneform bacteria	Yabaya, 2006; Ojewumi et al., 2016; Olaniran et al., 2020c
Ugba	Fermented African oil bean seeds	*B. subtilis*, *Staphylococcus* sp., *Micrococcus* sp., *Corynebacterium* sp., *L. plantarum*, *L. casei*, *L leichmannii*, *L. brevis*, *L. salivarius*, *L. jensenii*, *L. acidophilus*, *L. cellobiosus*	Sanni et al., 2002; Olasupo et al., 2016
Afiyo/okpehe	Fermented food flavoring condiments derived from *Prosopis africana* seeds. It can also be processed from peanuts, soya bean, oil bean, cowpea, or lentils	*B. subtilis*, *B. licheniformis*, *Bacillus pumilis*, *Staphylococcus* sp.	Evans et al., 2013; Adeyeye, 2017
Palm wine	Fermented sap of palm trees taken in form alcoholic beverage with strong recognition in several traditional rights	*Saccharomyces* sp.	Nwaiwu et al., 2016
Nono/nunu	Fermented food/drink/beverage which is the local equivalent of yogurt. Sold as food (fura de nono) by the Fulanis	*L. acidophillus*, *Bifidobacterium bifidum*	Owusu-Kharteng et al., 2017; Agyei et al., 2020
Wara/local cheese	Fermented soft cheese	*Lactobacillus* sp., *Lactococcus* sp., *Streptococcus* sp., *Pediococcus* sp, *Leuconostoc* sp., *Propionibacter* sp., *L. casei*, *L. fermentum*, *L. lactis*, *L. plantarum*, *L. jensenii*, *L. brevis*	Saliu et al., 2014
Ukwa	Fermented African breadfruit	*Bacillus* sp., *Micrococcus* sp., *Lactobacillus* sp., *Staphylococcus* sp., *Enterobacter* sp., *Aspergillus* sp., *Alternaria* sp., *Curvularia* sp.	Nwaneri et al., 2017

made from millet, maize, guinea corn, or rice using *L. plantarum*, *Lactobacillus cellobiosus*, *Lactobacillus pentosus*, *Leuconostoc mesenteroides*, and *P. pentosaceus* (Owusu-Kwarteng et al., 2017). Rural people are well known to derive health benefits from the consumption of fermented foods rich in probiotic microflora (Franz et al., 2014). The therapeutic applications of Nigerian indigenous foods have been documented by several studies. LAB isolated from several fermented foods produce antimicrobial agents and organic acids responsible for the preservation and palatability enhancement of the final product. Researches also showed the supportive role of LAB in the modulation of host immune system and prevention and treatment of diarrhea in addition to their antimicrobial activities against common foodborne pathogens (Capozzi et al., 2017). Common Nigerian fermented foods, such as *ogi* and *kunu-zaki*, reportedly have potential therapeutic effects that could reduce the risk of infections and diarrhea; moreover, they are known to suppress the growth of pathogens owing to their immunostimulatory effect *via* modifications in the gastrointestinal microflora (Olalude et al., 2021). The consumption of *iru* helps prevent poor vision and skin irritation (Taha et al., 2017). Fermented milk has a blood pressure-lowering effect and antimicrobial activities and is used to complement antibiotic courses. It is also a good source of antioxidants and essential amino acids. The responsibility of ensuring the accessibility of tasty, affordable, safe, and healthy foods is entrusted to microbiologists, agriculturists, food scientists, and various professionals in the food industry. Currently, there is an appeal for the deliberate introduction of biotechnology, especially the application of microbiomes, into the Nigerian local food processing to benefit the producers, modernize the food value chain, and increase income and at the same time help fast-track the sustainable consumption and production patterns of nutritious and safe diets.

CONCLUSION

Food is among the basic needs of humans and animals. The public acceptance of foods is significantly influenced by their nutritional quality, safety, and digestibility. While Nigeria has a plethora of locally fermented foods, it is opening up to the possible application of biotechnology in food production. During laboratory researches, several mechanisms for the production process of fermented foods have been established; however, lapses/huge gaps occurred between the research and the commercialization of advanced techniques, retaining the description of the production process of fermented foods in Nigeria as "traditional". To help mediate technology with the traditional handling of fermented foods in Nigeria, advocates for microbiological tests, and biotechnological applications are needed. These will provide locally fermented food manufacturers with acceptable batch analysis, accuracy, sensitivity, specificity, and all other standard characteristics required to ensure the safety of consumers. This may border on adapting microbial analytical assays to local food processing chains or scientific approach, and system biology in the innovative manipulation of existing traditional methods using genetic traits selection. The Nigerian government and the policy-makers should capitalize on these food assets and create value addition by supporting research, education, and development while improving the indigenous knowledge of food fermentation. The institutionalization of a national system that affords the regulatory certification of fermented food and the application of biotechnology will promote the development of locally fermented food products. The quest to apply biotechnology in the local food processing in Nigeria to improve the food value chain, revolutionize packaging for the retail market, and increase the income of producers is still ongoing. Such an application is expected to transform the "unhygienic" perception of some middle-/high-class individuals toward fermented foods in Nigeria and make these products attractive to a larger consumer market. Therefore, the development of this sector can afford promising potential and viable opportunities that can be economically harnessed for the nation's foreign exchange business (exports) and international market domination. Hence, there is a need to further sensitize local producers to promote traditional fermented foods as valuable assets.

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