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Fermented Foods: Functional and Regulatory Insights

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Abstract

Traditional fermented edible products have been in the food industry since ancient times. Today, the fermentation process has become most common in the health food industry. Due to the microorganisms present in fermented food products, the health benefits have been helpful in many ways. Fermentation helps in enhancing gut health, blood sugar, blood pressure, and brain health. These food products also play a major role in lowering cancer risk and heart disease. The processed and fermented food manufacturing sector has been gaining in CAGR over the years, and especially with onset of the Covid-19 pandemic. Many different food types are amenable for fermentation, such as tea, rice, meat, some vegetables, and many dairy products. To address the issue of prolonged storage of fermented products, it is essential to solve the issue of packaging and enhance the usage/shelf life of these products. Advancement in packaging technologies now play a key role in extending shelf life, preserving quality, and ensuring the safe delivery of fermented foods. This review focuses on some of the fermented products, global regulations for fermented edible items, health benefits, packaging and global regulatory frameworks and challenges associated with it.

Keywords: Fermentation, anti-microbial, anti-oxidant, anti-nutritive compounds, anti-inflammatory, regulatory framework, packaging

INTRODUCTION

Fermented beverages and foods are fundamentals of the fermentation food industry. The use of fermented food started with the mere purpose of increasing its shelf life. Evidence of fermentation dates back over 8000 years [1] when people intriguingly discovered spontaneous and lactic acid fermentation. Fermentation is an anaerobic process where, in the absence of oxygen, microorganisms convert carbohydrates into simpler compounds.

In today's world, the role of fermented foods has transcended mere preservation. Fermentation brings two components together: first is the enhancement of the nutrition in the food products, and second are the health benefits associated with it. Fermented foods and gut health are closely linked, which is another reason why the capabilities of fermentation were observed. For instance, individuals with lactose intolerance often find relief after consuming yogurt. Figure 1 shows the overall picture of fermentation, its benefits and challenges. Human dietary studies have also shown that fermented foods can reduce cardiovascular risks and aid in weight management. Fermentation leads to the growth of live microorganisms, which plays a major role in understanding their underlying benefits and risks.

Fermentation is a traditional method of preparing food and beverages that is deeply ingrained in various cultures around the world. The market fermentation will substantially investigate the increment of $1.24 trillion by 2034 with a compound annual growth rate of 8.1% [2]. India

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plays a major role in this market of fermented food because of the staple diet in most regions. Two-thirds of the Indian population is dependent on fermented food for their diet, and approximately 35% of Indian milk is processed [3].

The process of fermentation begins when a specific starter is added to the food product. These starters, which could be of various types, such as Lactic Acid Bacteria starters or Yeast starters, are often referred to as natural starters. However, starters are also used in the commercial production of fermented products.

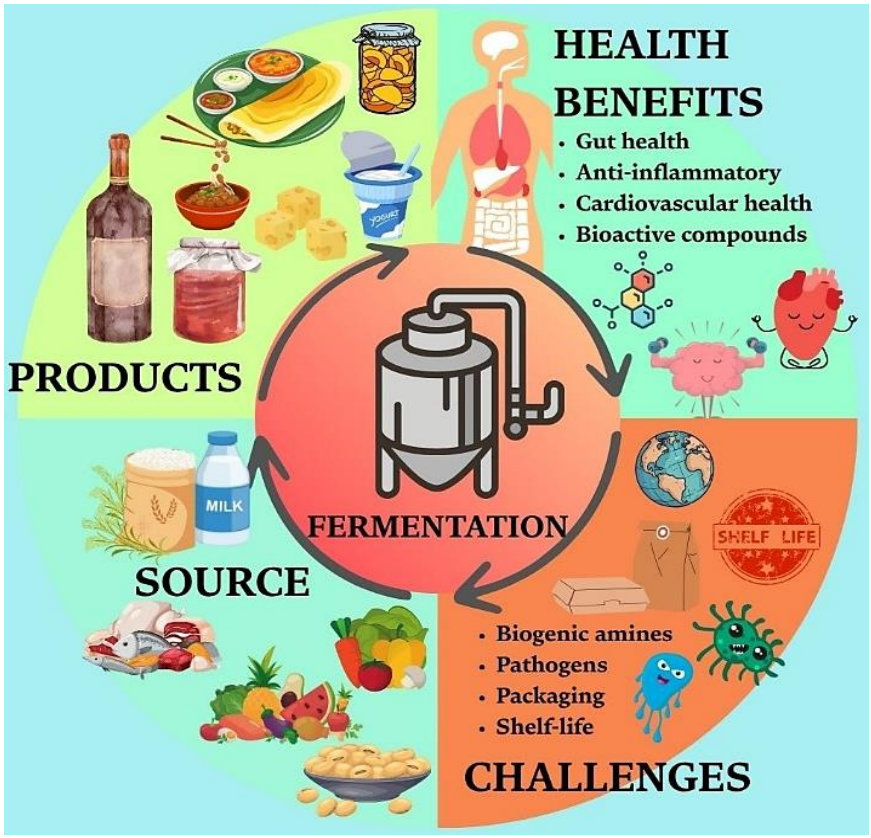

Figure 1. Fermentation – an overview of processes, products and challenges.

METHODOLOGY

This review was conducted by collecting scientific literature from trusted and peer-reviewed databases, including PubMed, ScienceDirect, NCBI (National Center for Biotechnology), and Google Scholar.

A comprehensive literature search was performed according to the relevance for the study of types of food that undergo fermentation, functional properties of fermented foods, packaging, global regulations, and challenges faced during the fermentation. The references selected were critically analyzed for scientific depth, relevance to the scope of the paper, and contribution to the current understanding of fermented food systems.

Traditional Aspects of Fermented Foods

Traditional foods and beverages that have been fermented have always been the center of attraction due to the presence of microorganisms in them. In 1955, Roberfroid, in collaboration with Gibson, was the first scientist to give detailed descriptions regarding prebiotics [4]. Probiotics are live microorganisms, usually bacteria or yeast that are beneficial for the host (human, animal, or plant) whereas prebiotics are non-digestible compounds that promote the growth of beneficial microbes [4].

Traditional fermented edible products are generally cooked in households using the available raw materials. Traditional food and beverages were reported to have unique properties: (a) prolonged shelf-life and preserved raw materials, (b) enhanced taste, (c) enhanced nutrition level in the food, and (d) health benefits [5]. Traditionally, food fermentation was widely used with raw materials that would have the above unique properties. Nowadays, industries use only one or two strains as their microbial starters because of the ease of reproducibility. There are various opportunities to seek traditional raw materials that can be used for fermentation.

Fermented products are broadly divided into three major categories: (a) alcoholic fermentation, (b) lactic acid fermentation, and (c) acetic acid fermentation. The fermentation that occurs with the help of lactic acid consists of lactic acid bacteria (LAB), which are primarily utilized for the fermentation procedure of yogurt, sausages, cheese, kimchi, kefir, and kombucha. Fungal fermentation can be observed in foods from Asia which are generally soy-based such as soy sauces and tempeh. Natto is observed to have alkaline fermentation [6].

High-throughput DNA sequencing has led to the discovery of various other microorganisms, including bacteria, yeast, and filamentous molds that are a part of fermented food. These include species of bacteria such as *Arthrobacter, Bacillus, Bifidobacterium, Enterobacter, Halobacterium, Klebsiella, Pseudomonas,* and *Staphylococcus*. The genera of yeast found are *Candida, Cryptococcus, Dekkera, Hansenula, Pichia, Rhodosposrium, Saccharomyces,* and *Trichosporon,* while the filamentous molds include *Ustilago, Actinomucor, Penicillium, Aspergillus, Mucor, Rhizopus,* and *Neurospora* [7].

TYPES OF FOODS THAT UNDERGO FERMENTATION

The three important factors that can classify the beverages and food products that undergo fermentation are: 1. the ingredients utilized for the fermentation procedure, 2. time taken for the process, and 3. the microbes used for the process.

Milk-Based Products

Most of the world is dominated by either milk or various other dairy products. The most important thing to understand is that most dairy items are manufactured due to the result of different pathways of fermentation that use lactic acid bacteria (LAB), which are made possible by a variety of microorganisms. There are three major types of fermentation, homo-, hetero-, and facultative fermentation [7].

Lactic acid is one of the essential end-products of fermentative metabolism, and it occurs due to the lactic acid bacteria, a batch of gram-positive bacteria. Lactic acid bacteria (LAB), such as *Lactobacillus, Lactococcus, Leuconostoc, Pediococcus*, are used as fermentation starters for cheese fermentation. These bacteria can convert the sugar made up of two linked monosaccharides, lactose, into lactic acid. The cheese is then solidified with the help of the rennet enzyme. Rennet enzyme is produced in the young ruminant animals' fourth stomach lining.

In India, yogurt is commonly called Dahi and is made in the household. Preparing Dahi requires a starter culture from the previous batch. Other forms of Dahi used in India are lassi and sour milk.

Greek yogurt has ample popularity in Western culture, and it has its fermentation procedure. The bacteria used to ferment Greek yogurt are *Streptococcus thermophillus* and *Lactobacillus bulgaricus* [6].

Batzos Greek cheese is also one of the most used dairy products. It is majorly dominated by lactic acid bacteria (LAB), such as *Lactococcus lactis, Lactobacillus plantarum, Lactobacillus paraplantarum, Lactobacillus paracsei,* and enterococci, such as *Enterococcus faecium,* and *Enterococcus durans.* Other microbes also include enterobacteriaceae, coliforms, staphylococci, and yeasts [8].

Fermented Beverages

The beverage industry is one of the biggest users of fermentation. Depending on the volume of alcohol present in a beverage, it can be alcoholic or non-alcoholic. While non-alcoholic beverages have amount of alcohol less than 0.5% v/v, alcoholic beverages have a higher amount of alcohol that is more than 0.5%v/v [6].

Whiskey, vodka, and beer are generally prepared by fermenting grains such as barley, corn, rye, and millet. Ginger beer, ginger ale, wine, and ciders are prepared by fermenting fruit juices. Potatoes and sugarcane help in the fermentation of rum and vodka [6].

Kombucha is a global, non-alcoholic fermented drink that is a sweetened tea. It contains SCOBY, or a Symbiotic Culture of Bacteria and Yeast [9]. The genera, *Acetobacter*, *Gluconobacter*, and *Gluconacetobacter*, consist of acetic acid bacteria that can be majorly found in Kombucha.

Kefir is another such fermented beverage that comprises of 83–90% of lactic acid bacteria such as *Lactobacillus, Leuconostoc,* and *Streptococcus* species. Acetic acid bacteria and yeasts, such as *Saccharomyces* and *Kluyveromyces*, are predominated [10].

Sourdough

Sourdough is among the most famous fermented foods in the world. Its fermentation is quite simple, requiring flour and water. Sourdough has different versions in different countries but is quite famous in Italy, Milan, and San Francisco. In India and Sri Lanka, sourdough is used to make Idli and Dhokla [6].

Sourdough utilizes heterofermentative strains of Lactic acid bacteria (LAB). Cereal phytases are activated to make the nutrient compounds bio-available, and the deactivation of flour's a-amylase is also observed.

The microbiome of sourdough is dominated by lactic acid bacteria (LAB), such as *Lactobacillus platarum, L. fermentum, Weissella, Leuconostoc*, and *Pediococcus*, as well as yeasts, like *Saccharomyces* and *Candida*, are present in a LAB-to-yeast ratio of 100:1 [11].

Fermented Meats

Meat fermentation is a crucial procedure, mostly done in northern regions, to increase the storage period and enhance the flavors. The fermentation process enhances nutritional value and reduces cooking time. Meat fermentation is done with the help of LAB or (CoNS) coagulase-negative staphylococcus [6].

Fermented meats are a host to probiotic strains, like *Lactobacillus plantarum, L. rhamnosus, L. paracasei, L. acidophilus, L. sakei, Limosilactobacillus fermentum, Enterococcus faecium, Bifidobacterium longum,* and *Staphylococcus simulans*, that survives the processing and packaging process. These microbes also contribute to product safety, shelf life, and potential health benefits [12].

GUT MICROBIOME

The gastrointestinal tract consists of complex and vigorous varieties of microorganisms that can either influence the host to maintain balance or protect it from diseases. Fermented foods have been greatly reported to be helpful in improving gut health. The gut microbiome is capable enough to treat and save the human body from potential diseases. Obesity and hypercholesterolemia have already been reported to be prevented in possible patients. Bacteria, such as *Bifidobacterium breve*, *Lactobacillus*, and *B. bifidum*, can produce conjugated linoleic acid with the conversion of linoleic acid, which has been investigated to suppress carcinogenesis [6].

It has been observed that the traditional method of fermenting food is more effective in boosting gut health than store-bought products. Obese women who are a survivor of metabolic syndrome face insulin resistance, traditional fermented foods have reportedly decreased the resistance [1].

The gut microbiome was reported to contain *Prevotella* species, which starts the breakdown and digestion of dietary polysaccharides. It is a plant-based species with a high fiber content. Many other species of this genus help in the digestion of vegan, vegetarian, and Mediterranean diets. *Prevotella* can also be labeled as a lifestyle biomarker due to its increase in number in the gut after consumption [1].

Fermented food consists of *Bifidobacterium* and *Lactobacillus,* which are observed to bring positive changes in the gut and are helpful in digestion and gut health. They are also known to reduce microorganisms, like *Clostridium perfringens*, that are harmful to health [1].

It is duly observed that a nutritious diet rich in fermented foods and fibers can improve mental health. Mental health and stress are the most common causes of irritable bowel syndrome. The intake of fermented food products can significantly improve neural networks, brain activity, and mood.

Fermentation increases the availability of polyphenols in food products. Polyphenols consist of flavonoids and phenolic acids. They have a great influence on the gut and can also increase their antioxidant properties. Polyphenols also help inhibit pathogenic bacteria [7]. Tea is one beverage that contains flavonoids.

The gut microbiome efficiently converts the compounds present in fermented food and improves gut health. Fermented foods have been proven to protect the gut from gastrointestinal disorders, infections, allergies, and Crohn's disease [7].

Recent high-throughput sequencing technologies, such as 16S rRNA gene amplicon and shotgun metagenomic sequencing, have enabled the possibilities to study the detailed profiling of gut microbiome due to fermented foods. It was also understood that there are numerous uncultivable microbes that play a major role in this process. Chan et al. used Illumina MiSeq-based 16S rRNA sequencing and in vitro colonic fermentation models. It was witnessed that the product formed from fermented vegetables, like sauerkraut and tibicos, increases the number of butyrate-producing bacteria called *Megasphaera* in gut which can potentially be used for the treatment of insulin sensitivity, and irritable bowel syndrome. Additionally, the number of microbes, such as *Lactobacillus, Leuconostoc, and Pediococcus*, increase substantially [13]. These results indicate that fermented foods introduce not only cultivable but also uncultivable microbes into the gut, which perform health-supportive functions.

Leech and co-workers used shotgun metagenomics to analyze 58 different fermented foods and identified 127 high-quality metagenome-assembled genomes (MAGs). These included several new and uncultivable species, such as *Acetobacter, Acidisphaera, Gluconobacter, Companilactobacillus, Leuconostoc,* and *Rouxiella* [14]. The functional annotation of these MAGs states that these microbes are involved in carbohydrate metabolism and antimicrobial resistance. A recent study conducted by Yumnam, metagenomic study on traditional rice-based fermented beverages that highlights the importance of meta-transcriptomic studies to understand real-time gene expression and functional role of cultivable and uncultivable genera such as *Pediococcus, Leuconostoc, Weissella, Lactococcus, Bacillus, Steptococcus, and Enterococcus.* Opportunistic pathogens, like *Staphylococcus* and *Klebsiella*, were also found in his study [15]. Hence, it is important to integrate meta-transcriptomics with metagenomics, so that the connection between gut microbiota after the intake of fermented foods and host health can be understood clearly.

MICROORGANISMS' CHARACTERISTICS IN FERMENTED FOODS

Fermented food products have various functional properties that help improve health. This review mentions antimicrobial, antioxidant, peptide production, and degradation of antinutritive compounds.

Antimicrobial Properties

Antimicrobial properties are the ability to inhibit or kill microorganisms. Bactericidal properties refer to the killing of bacteria, whereas bacteriostatic properties refer to the growth inhibition of microorganisms.

Fermented food products strongly show antimicrobial properties. Anti-microbial compounds, like nisin and bacteriocin, are produced with fermentation [16]. Bacteriocin functions by degrading the cell membrane and inhibiting cell functions, eventually leading to cell death. Nisin forms pores in the bacterial cell membranes, leading to cell death.

Fermented food products, such as kimchi consist of *Lactococcus lactis* BH5 and *Leuconostoc citreum* GJ7, which are reported to produce bacteriocin. *Staphylococcus aureus*, *E. coli*, and *Salmonella typhimurium* can be inhibited due to this anti-microbial activity. The lactic acid bacteria found in Indian curd can inhibit the activity of *Staphylococcus aureus*, and *Listeria monocytogenes.* Fermented fruits and vegetables have been reported to isolate *Weissella cibaria* and other lactic acid bacteria. They can inhibit the anti-microbial activity against various other gram-positive and gram-negative pathogens such as *E. coli*, *Salmonella*, and *Bacillus* [17].

Antioxidant Activity

Antioxidant activity works on the principle of donating an electron to the free radical so that it can neutralize the activity. This helps protect the organism from cellular damage. Fermented foods show a great variety of range in compounds, which are antioxidants. *Bacillus*-fermented soybean food is available in Japan, Nepal, Thailand, and India [17]. Bacillus species can disintegrate soybean proteins into much smaller peptides and amino acids, which can fight oxidative stress [18].

Similarly, after the fermentation of kimchi, bioactive compounds, such as phenolic compounds and flavonoids, are produced. They cumulatively tend to boost the antioxidant capacity. Yogurt is rich in antioxidants because of fermentation. The fermentation process enhances the production of vitamin B, which has antioxidant effects [19].

Degradation of Anti-Nutritive Compounds

Anti-nutritive compounds are synthetic compounds found in food products. They reduce the body's ability to absorb, digest, and utilize nutrients, disrupting its proper functioning [20]. Fermented foods have the potential to reduce the amount of anti-nutritive compounds in the food product and form those compounds into consumable substances. Cassava is an African food product that, after fermentation, produces gari and fufu. Cassava contains various anti-nutritive compounds such as lotaustralin, linamarin, and cyanogenic glycoside [17]. These compounds are decontaminated after the process of fermentation by *Leuconostoc*, *Lactobacillus,* and *Streptococcus*.

ANTI-INFLAMMATORY PROPERTY

Anti-inflammatory properties are beneficial in reducing inflammation in the body. Inflammatory conditions such as cardiovascular diseases and gastrointestinal diseases.

Soybean fermentation leads to the formation of miso or tempeh, which increases the production of flavonoids and polyphenols. These compounds decrease inflammation. Fermented dietary products produce butyrate, which reduces colon inflammation and improves gut health [17].

Packaging of Fermented Food Products

The global market for fermented foods and beverages has increased insignificantly. Packaging fermented functional foods and beverages is important to prevent contamination and ensure safe transportation. The primary goal of the packaging team is to keep up with the distinct flavors, textures, and nutritional value and to prevent contamination. Due to current packaging trends, consumers have started to have their preferences for sustainable packaging materials which can be used for both fermented probiotic dairy and non-dairy food and beverage products.

Polyethylene (PE), which is composed of ethylene polymer, is commonly used for the packaging of yogurt cups, milk, buttermilk, and kefir bottles. PE is known to be durable. Polyethylene terephthalate

(PET) is used for the packaging of milk bottles, cheese packaging, and yogurt cups, and it creates a barrier to moisture and gases. Low-density polyethylene (LDPE) and High-density polyethylene (HDPE) are used for the packaging of food and beverages, which saves them from UV contamination [21].

The packaging materials that can decompose naturally are called compostable packaging materials, such as biodegradable plastics or plant-based materials, which are the current trend. Polylactic acid (PLA) is the current center of attraction for the biosynthesis of lactic acid from potato-processing wastes [21].

The packaging industry's prospects include addressing the issues that might occur after packaging. The first problem is oxygen, which leads to food deterioration. Active packaging solutions are trying to incorporate oxygen scavengers, which can absorb oxygen and reduce oxidative stress [22]. Anti-microbial films are also being studied, which will provide an extra layer of protection against harmful microorganisms in food. These anti-microbial films are prepared from edible plant material like aniseed. Fermented food products have become global, and packaging is the next correlated part [21].

GLOBAL REGULATIONS

Fermented foods have become a global identity, and because of their increased usage worldwide, it has become important to establish a global framework. Due to geographical differences, cultural inheritance, and microbiome availability, the process of fermentation is slightly different in different regions. The regulatory frameworks are used to understand the regulations associated with fermented foods.

Codex Alimentarius Commission, the World Health Organization, and the United Nations Food and Agriculture Organization have constitutively formed The Codex Alimentarius. The fourth revision was made in 2018 by Codex Alimentarius, which provided guidelines stating that fermented milk is a component of milk and is modified due to suitable microorganisms [23]. As of the year 2022, Codex recommended that the labeling is a concern and must be addressed as a priority. That is how, on July 1, 2022, food labeling regulations came in, which stated that all food products that could be allergens must be included in the label [24].

In Europe, the General Food Law Regulation must ensure that human life is protected regarding any kind of food. The European Food Safety Authority (EFSA) has already maintained its scientific opinion regarding the risk assessment of food products formed with fermentation. It stated that fermented food products should be considered novel foods. The Nutrition and Health Claims Regulation has given its verdict that the microorganisms present in yogurt are beneficial for lactose digestion [23]. In 2020, Safety Food for Infants came into place to investigate all the aspects of food products suitable for infants. This project was directly financed by the European Commission [25].

The Russian Federation has a Federal Law that briefly describes the requirements for producing food. In 2010, the country stated its compliance with the manufacturing and packaging process [23]. The Russian Government spread its framework of policies called Concept 2020, which increased the healthy nutrition aspect of food [26].

The USA has its (FDA) Food and Drug Administration, which has identified fermented foods as acidified foods. The FDA has briefly described yogurt as a dairy product after fermentation. The FDA also published guidelines regarding manufacturing, packaging, storage, and the eligibility criteria for being referred to as fermented foods. In 2021, the Laboratory Accreditation for Analyses of Foods program was established to keep the food in a standardized form [27]. In Canada, the FDA has approved live microorganisms as a food product [21]. In 2012, the regulatory body of the Safe Food for Canadians Act was introduced, which consists of all the food laws under one umbrella [28].

Japan has a Food Sanitation Act that states that every lactic acid bacterium is a probiotic and is permitted to be. These are edible products and do not require any kind of clinical trial; only the government's approval is acceptable. In 2018, Japan has amended its laws on functional foods [23].

India has established its own Food Safety and Standards Authority of India (FSSAI), which has implemented all the standards regarding manufacturing, storage, packaging, and transportation. The regulation of fermented milk is also addressed to ensure an acceptable composition. The Food Safety and Standards also noted that food products that have added probiotics are considered novel foods. These safety guidelines were last amended in 2018 [23]. In 2024, laws regarding labeling requirements were passed for vegan foods [29].

There are a variety of challenges faced by food safety lawmakers to maintain compliance with all the regulations. Clerks who are not well-trained fail to follow the standard operating procedures of the food supplies. Despite the awareness for the cooking and storage methodology of food, food safety regulations cannot micro-manage every step of the food making process. Mishandling of the food supplies is possible at every step until it reaches the consumer. That is why it is necessary to collaborate with the people associated with the food manufacturing, packaging, transportation, and handling [30].

CHALLENGES

Microorganisms are known to create an environment that is hostile to several other microorganisms. Fermentation itself acts as a first line of defense for pathogenic bacteria by decreasing the pH values and removing carbohydrates from the environment. This leads to a shortage of nutrients for the competition. The safety issue arises in the timeline until the defense line is created. Fresh cheese of artisan origin is reported to have *Brucella,* which can cause foodborne diseases. The ripening process of the cheese generally kills the pathogens and enhances the antibacterial and antioxidant activities. It is still not sure that microorganisms will be inactivated because it is observed that *Staphylococcus* is one such bacteria that survives the ripening and fermentation technique [6].

Biogenic amines, produced from fermented products, can cause major health risks. Cheese, beer, wine, and fish products undergo microbial decarboxylation of precursor amino acids to produce biogenic amines. Enterobacteriaceae and enterococci are the primary producers of biogenic amines such as histamine and tyramine. If they are more than 100 mg/kg [30], they can cause food-borne diseases and poisoning in the body.

It is also observed that *Acetobacter, Glutanobacter,* and *Glutanacetobacter* are helpful for acid production in vinegar, but their presence can spoil the wines and cause microbial infections in the body [31].

CONCLUSIONS

Fermentation is one of the oldest techniques, but it has evolved with modern health concerns. The initial reason for fermentation was to increase the shelf life of food. People have accepted fermented food and beverages as functional food due to their health benefits. The microorganisms present in fermented food and beverages create a gut microbiome that keeps the gut healthy. This literature review gives a brief idea about the food products that are fermented all around the world such as dairy products, alcoholic and non-alcoholic beverages, meats, vegetables, and cereals.

Fermented foods and beverages are a major source of probiotics. They also have antioxidants, antimicrobials, and anti-inflammatory properties. Due to these health benefits, various organizations worldwide have formed a global regulatory framework to ensure consumer safety. However, these functional food products do have some health risks associated with them, such as biological amines, that need to be resolved. This also gives us a brief idea about the importance of safer fermentation practices.

As the demand for fermented food increases globally, innovative packaging solutions are becoming the need of the hour. Research is already ongoing on biodegradable packaging material options that would keep food products secure and maintain quality. Fermentation is a vital food industry, and culinary traditions will continue to grow to benefit humans.

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