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PLANT-BASED FERMENTED FOODS: A REVIEW OF MICROBIOLOGICAL, BIOCHEMICAL, AND SENSORY PROPERTIES

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Abstract

Plant-based fermented foods have gained increasing attention due to their health benefits, enhanced nutritional value, and improved sensory properties. Fermentation plays a crucial role in modifying the biochemical composition of plant-based foods, leading to the production of bioactive compounds, improved digestibility, and the reduction of antinutritional factors. The microbiological aspect of fermentation is essential, as diverse microorganisms, including lactic acid bacteria, yeasts, and molds, contribute to flavor development, texture modification, and extended shelf life. These microbial interactions lead to complex biochemical changes, including the breakdown of macronutrients, the synthesis of vitamins and antioxidants, and the formation of unique flavor compounds. Sensory attributes such as taste, aroma, texture, and color are significantly influenced by fermentation, affecting consumer acceptability. Despite these advantages, challenges such as standardization, safety concerns, and variability in fermentation processes limit the large-scale application of plant-based fermented foods. Additionally, there is a need for further research on optimizing fermentation conditions, ensuring probiotic viability, and enhancing functional properties. Future advancements should focus on integrating biotechnology, improving microbial strains, and developing innovative fermentation techniques to create sustainable and nutritionally superior plant-based products. This review highlights the microbiological, biochemical, and sensory aspects of plant-based fermented foods while identifying research gaps and potential areas for future innovation.

Addressing these challenges will help expand the diversity and marketability of plant-based fermented foods, catering to the growing demand for functional and sustainable food alternatives.

INTRODUCTION

Fermented foods have been an important component of human diets all around the world. They are still widely consumed, but refrigeration and other habits in industrial food processing have put the consumption of these foods under pressure[1]. There exists a huge variety in fermented products, due to the diversity in raw materials or substrates on which the fermentation is performed or different process parameters. This variety is also reflected by the diversity of microorganisms that drive the fermentation processes as main biological actors[2] . Organisms from all three Domains of life are crucial to the taste, texture, and smell of the fermented end product. For example, strains from the yeast Saccharomyces cerevisiae are indispensable for baking bread and brewing beer. Lactic acid bacteria (LAB), contrastingly, are the key bacteria in the fermentation process of cheeses, yogurts, and fermented vegetables [3]. plant-based fermented foods are of interest, not only because of the probiotic and industrial potential of their microbes but also because they have been recently proposed as alternative non-dairy food matrices for probiotic administration. In contrast to their dairy alternatives, plant-based fermentations are suitable for lactose-intolerant, milk-allergic, or vegan people, and are appealing because vegetables are a source of essential nutrients, vitamins, minerals, antioxidants, and fibers, and they have a low sugar content . The food product itself could thus be used as a new carrier for traditional (dairy-based) marketed probiotics, enabling access to a new consumer market Furthermore, plant-based fermentations are of interest because of the microbes that drive these fermentation processes (Figure 1). Especially fermented foods of which the microbial communities are poorly characterized remain a rich source of untapped microbial diversity. However, recently due to a more widespread availability of DNA sequencing technologies, a shift from culturebased to sequencing-based techniques can be observed in studies that explore this diversity. While these cultureindependent techniques have their own advantages, for the selection and characterization of new industriallyrelevant strains, it is of course necessary to obtain physical isolates. For example, for the cultivation of LAB, a bacterial group that has many examples of industrialized probiotic strains, usually MRS-medium (de Man, Rogosa, and Sharpe medium) is used, with or without the addition of vitamin solutions [4]. Fermented foods and beverages have played a critical role in human history and prehistory and continue to be highly valued by human societies. Annual sales of fermented beverages alone exceed $2 trillion [5]. In addition, the human control of fermentation in order to produce and use what are, in essence, microbial farms, likely predates agriculture [6]. Potentially by hundreds of thousands of years [7]. Over the course of human history fermentation has helped ensure the safety of foods and beverages and has also shaped the sensory characteristics of our food. Cultures have come, again and again, to appreciate the tastes, aromas, and textures of fermented foods that signal their safety and nutrition. However, we lack a general model for understanding (*a*) when and why technologies associated with fermentation emerged and (*b*) how those technologies and the microbes associated with them diverged and evolved once they emerged.To microbiologists, fermentation is any microbiological process that converts carbon compounds to energy in the absence of oxygen. In the context of human food, we tend to consider fermentation to be the subset of those conversions that yield foods and drinks that humans intentionally ingest. Such fermentations rely on diverse bacteria, fungi (including yeasts), and, more rarely, archaea [8]. Fermentations can be separated into two larger categories: acidic and alkaline fermentations (or “ferments”). Acidic ferments are those primarily driven by acid-producing bacteria and include products such as sauerkraut, pickles, and kombucha. Alcoholic fermentations are often a form of acidic fermentation inasmuch as they typically include acid-producing bacteria and yield products that are both alcoholic and acidic. Alkaline ferments, on the other hand, include tempeh, a subset of mold-ripened cheeses, and lutefisk (a traditional Nordic dish of fish fermented in lye). Fermented foods and drinks can also be divided as a function of the substrate being fermented. Many fermentations rely on protein. Protein ferments include fermented meats, fish, legumes, and nuts. Other fermentations begin with carbohydrates. Carbohydrate ferments are represented by fermented cereals, tubers, vegetables, fruits, and dairy products. A third group of fermentations is based on animal fats; such fermentations are often used to add desired flavors to butter or lard .The diversity of individual types of fermented foods differs among cultures and geographic regions . In some regions and cultures, the only foods that are fermented are meats, whereas in other cultures and regions, other proteins, carbohydrates, and fats are all fermented.The number of varieties of individual types of fermented foods also varies. Fermented foods also, of course, have other sorts of geographic and cultural patterns that deserve explanation, on which we will not focus here. For example, the proportion of dietary food intake made up of fermented foods varies geographically [9] . In some cultures and times, most major staples are, or were, fermented. In medieval monasteries in Europe, for example, nearly all dietary calories came from bread (fermented with sourdough starters), wine (fermented with yeasts), and cheese (fermented with diverse communities)[10]. In other cultures, fermentation is more marginal. Yet this pattern, like others related to fermented food, has been essentially unquantified, whether for prehistoric, historic, or modern times.The fermentation process was used to preserve the milk and make it more palatable. This allowed for the production of a variety of dairy products such as cheese, yogurt, and kefir. Societies during the Neolithic period consciously preferred to consume different animals' milk for cultural and taste reasons and processed this milk in various ways [11]. Traditional fermentation has been employed for centuries in raw milk processing. The process is spontaneous, and part of the fermented product is used to inoculate the new batch. In contrast, non-traditional fermented milk products have recently been developed. These products are produced with known microbial cultures based on scientific principles, and their quality can be optimized [12]. Non-traditional fermented milk products are more consistent in quality as the addition of known microbial cultures creates a more controlled fermentation process. This process also ensures that the products are standardized and free of any potential health risks associated with raw milk. It has been reported that probiotic-based fermented functional foods are becoming increasingly popular since the early 2000s [13]. From the past to the present, fermentation practices have been influenced by various factors such as raw materials, climatic conditions, production area, social, cultural, religious, and economic aspects . These factors have helped to shape the diversity of fermented products, and have also helped to influence the consumption of probiotic-based fermented functional foods. The popularity of these foods has been further strengthened by the health benefits associated with them, such as improved digestion, increased nutrient absorption, and enhanced immunity. Milk and dairy products are now consumed worldwide, primarily in pasteurized and fermented forms. However, variations in consumption rates are caused by per capita income and the impact of regional preferences . This is due to the fact that those with higher incomes can afford to purchase more nutrient-rich foods and have access to a variety of different ingredients to choose from. Additionally, regional preferences play a significant role in the demand for certain food items, as people's taste and cultural preferences vary from one region to another.

Fermented foods with live microorganisms include yogurt, kefir, cheeses, miso, natto, tempeh, kimchi, kombucha, and some beers . Some foods are subjected to pasteurization, smoking, baking, or filtering after fermentation, causing live microorganisms to die or be removed. Sourdough bread (baked), shelf-stable pickles (heated), sausages (heated), soy sauce (heated), vinegar (heated), most beers, distilled spirits (filtered), coffee and chocolate beans (roasted) are fermented products . Still, microorganisms have died or been eliminated from fermentation. Foods such as fresh sausages, vegetables preserved in brine or vinegar, processed soy sauce, non-fermented dried meats and fish, and acidified cottage cheese are not considered fermented, as live microorganisms are not involved in production. Fermented foods are sometimes called “probiotic foods” or “probiotics” and are used interchangeably. However, using these definitions interchangeably is incorrect. Probiotics contribute to their beneficial effects when administered in sufficient quantities. They do not have to take a specific form to have a positive effect on the host. Probiotics are live microorganisms that have a beneficial effect on the host, while fermented foods are simply foods that have gone through a process of fermentation . The probiotic benefits of fermented foods come from the live microorganisms present in the food, which are not always present in sufficient quantities to have a positive effect on the host. Molecular components of probiotic-containing foods show prophylactic or therapeutic effects against disease-causing agents. These foods are generally known as nutraceuticals, foodiceuticals, functional foods, or medifoods . These foods interest consumers based on their nutritional and organoleptic properties and beneficial effects on human health [14] . The effects of these foods are attributed to the presence of bioactive compounds, which can be of plant or microbial origin. These compounds, such as antioxidants, polyphenols, vitamins, and minerals, have protective effects against disease-causing agents like bacteria and viruses.

The fermentation process produces large quantities of lactic acid, alcohol, or acetic acid that inhibit other microorganisms. They also continue to reproduce unaffected by these generated substances, a process known as “amensalism” [15]. These by-products generated by the fermentation process are toxic to other microorganisms, making them unable to reproduce. This gives the fermenting microorganisms a competitive advantage, allowing them to outcompete other microorganisms in the environment. Fermented products are usually thicker than milk because acid precipitates milk proteins. Pathogens are inhibited by high acidity and low pH. Fermented dairy products have a unique, desirable flavor, texture, aroma, and improved digestibility compared to the raw materials they produce. However, the wrong fermentation process poses a health hazard. Unhygienic conditions or improper food production lead to contamination and spoilage. Foodborne disorders are brought on by spontaneous fermentation by unidentified microbes, which promotes the growth of undesired and even hazardous microorganisms . This can cause food to be unsafe to eat, leading to food poisoning. Symptoms of food poisoning can range from mild to severe, and can even be life-threatening. Therefore, food producers need to take proper steps to prevent contamination and spoilage.Propionic acid bacteria (PAB) and lactic acid bacteria (LAB) are microorganisms utilized to make cheese and other fermented dairy products. LAB is used to acidify milk, and PAB is used for its aromatizing properties . Propionic acid bacteria are microorganisms that produce propionic acid and are involved in producing fermented propionic cheeses, such as Swiss cheese, with exceptional adaptability to technological and physiological stress conditions. The propionic acid fermentation in cheese causes characteristic pores, cracks, and a slightly sweet flavor. Propionic acid bacteria are also responsible for the formation of carbon dioxide during the fermentation process, which gives cheese its airy, spongy texture. This also contributes to the flavor of the cheese, as the carbon dioxide imparts a slightly sour taste. Propionic acid bacteria metabolism differs significantly from lactic acid microorganisms. It is characterized by the production of carbohydrates during fermentation, except for lactic acid, propionic acid, and acetic acid . As a result of PAB's metabolic activities, the product is enriched with organic acids, vitamins (B2, B12, K, and folate), and other nutrients, increasing the stability and nutritional value of food products . Fermented dairy products provide an ideal environment for probiotic bacteria to grow in the human gut. LAB include *Lactobacillus*, *Streptococcus*, *Lactococcus*, *Bifidobacterium*, *Leuconostoc*, *Enterococcus*, and *Pediococcus*, which are among the most common strains of probiotic bacteria found in fermented dairy products . In addition, yeasts and molds such as *Debaryomyces*, *Kluyveromyces*, *Saccharomyces*, *Geotrichum*, *Mucor*, *Penicillium*, and *Rhizopus* species are employed as fermenting microorganisms [16]. Fermented milk products are prepared using different starter cultures, and the types of microorganisms used in production are specified in the regulations (Table 3). Fermentation preserves probiotic properties while maintaining microbial viability and production [17]. This helps to ensure that the fermented milk products are safe to consume and that they have the desired probiotic properties. This is because the starter cultures help to control the growth of unwanted microorganisms while promoting the growth of beneficial ones. The objective of this review is to provide a comprehensive analysis of plant-based fermented foods by exploring their microbiological, biochemical, and sensory properties. Fermentation plays a crucial role in enhancing the nutritional value, shelf life, and sensory attributes of plant-based foods, making them more appealing to consumers. This review aims to highlight the key microbial strains involved in fermentation, their biochemical transformations, and the resulting impact on flavor, texture, and health benefits. While extensive research has been conducted on traditional dairy-based fermented foods, plant-based alternatives remain underexplored, particularly in terms of standardized fermentation processes, microbial diversity, and their influence on functional properties. A significant research gap exists in optimizing fermentation conditions for different plant matrices, ensuring product consistency, and enhancing probiotic potential in non-dairy fermented foods. Moreover, limited studies focus on consumer acceptability and sensory modifications in novel plant-based fermented products. Addressing these gaps is essential for advancing the field and developing innovative, sustainable, and nutritionally enhanced plant-based fermented foods that cater to the growing demand for dairy-free, functional food options.

Microbiology of Fermented Foods

The process of fermentation, along with the processes of drying, smoking and salting, is one of the oldest methods of food and beverage preservation and of improving their nutritional value. Fermentation is a biotechnology that promotes and controls the growth of microorganisms and their metabolic activities for the preservation and transformation of raw food materials[18]. Therefore, today, when one considers fermented foods, it is not surprising that the focus is on foods in which microbial activity plays an essential role in obtaining the required stability, safety and sensory properties [19]. This discussion excludes those products that are often described as fermented but are largely the product of non microbial, enzymatic processes, such as black tea and Southeast Asian fish sauces, but should include those products such as tempeh and vinegar, in which the main microbial activity is not that of fermenters . However, when the discussion comes to the virtues of fermentation as a preservative, it is almost always related to those foods where lactic acid bacteria (LAB) play a central role in the production process .

There are two types of fermentation (regarding the way the fermentation microorganisms are utilized) :(A) **Natural fermentation:** A fermentation in which the fermentation microorganisms are already part of the natural microflora present in the foodstuff, so they do not need to be added. The only thing required is to create the necessary conditions for their development (e.g., the creation of anaerobic conditions, as in the production of pickles or olives), or the suppression of competing microflora (e.g., with the addition of salt or vinegar to the products) .

(B) Controlled fermentation with starter cultures: A fermentation that starts with the addition of a suitable inoculation with a large population of the desired fermentation microorganisms, necessary when the raw material is pasteurized (e.g., pasteurized milk) or when it is difficult for the desired fermentation microorganisms to prevail over competing microorganisms (e.g., in beer brewing, where wild yeasts may prevent the alcoholic fermentation by the strains of *Saccharomyces*). The starter culture contains the natural fermentation agents already present in the microflora of the food, but in much higher concentration than normal, to ensure that they easily prevail over competing–spoiling microorganisms. Therefore, with the addition of a starter culture, we better ensure a smooth fermentation process, the prevention of spoilage and the standardization of the product (steady qualitative and organoleptic characteristics) .

Today, fermentation is no longer simply considered a method of food preservation. Through time, man has managed to control the fermentation process, and fermented food now constitutes a separate sector of the food industry . In Germany, for example, approximately 25% of consumers prefer fermented food [20]. As a result of fermentation, the taste, smell, appearance, structure, texture, lifespan and safety of fermented food has different qualities compared to the raw materials from which they are produced . For example, the reduction of pH in meat paste can be achieved with the addition of Glucono-delta-lactone (GDL) or through fermentation . In both cases, the products are safe for consumers and have the same shelf-life and coherence stability, but the distinctive, desired taste of the final product can only be achieved through fermentation .

In addition, consumers have been consuming fermented food and beverages for a very long time, being aware that, in the process, they are ingesting billions of living cells of specific microorganisms or/and the metabolic products of these microorganisms without fear for their health and safety. This fact highlights the resilience of consuming fermented food through time and encourages researchers to continue their never-ending efforts to document the microflora of fermented food and find antimicrobial compounds that may be naturally present in such food . They can then research the possible use of such preserving agents as natural bio-preservatives, instead of chemical preservatives in other food products .

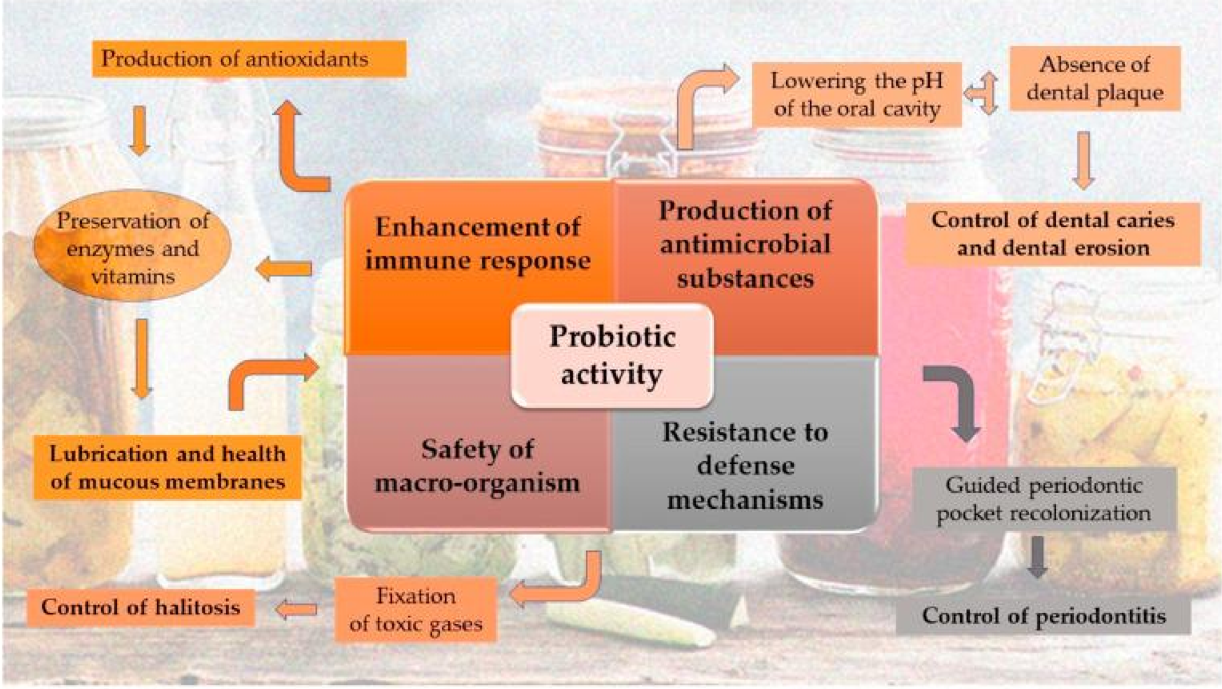


Figure 1: Mechanisms and advantages of action of fermented foods in the oral cavity.

Enrichment and Changes of Biological Components in Fermented Foods

Vitamins Bio-Enrichment

As a public health measure, nutrients, mainly vitamins, are fortified in some selected, manufactured foods; for example, vitamin D is added to milk and riboflavin during bread production, whereas ascorbic acid (vitamin C) can be fortified in fruit juices (Figure 2). However, this fortification or enrichment process can only be used in the Western world because of its high-cost value. Hence, most countries should use this type of food fermentation for the biological enrichment of foods [21]. There is a deficiency of thiamine (Vitamin B1) caused by using highly polished white rice. This type of rice can cause beriberi, a disease that leads to strokes and paralysis . Infants fed by thiamine-deficient (lead to beriberi) mothers can also suffer sudden death at three months because of heart failure . Thiamine is synthesized by the microorganisms involved in the tape Ketan fermentation. These microorganisms are also responsible for the restoration of the thiamine level found in unpolished rice . Therefore, this can be of great help to rice-eating individuals.An Indonesian origin-rich dish known as “Tempe” is prepared by soaking, dehulling, and partial cooking soya beans with the help of Rhizopus oligosporus or similar molds . This mold forms a firm cake by knitting cotyledons into slices and being cooked. There is the partial hydrolysis of proteins during the fermentation process; the lipids are hydrolyzed to their constituent stachyose (a tetrasaccharide indigestible by humans), fatty acids, riboflavin doubles, niacin increases by seven-fold, and vitamin B-12, usually absent in vegetarian foods, is synthesized by a fermenting bacterium growing with the essential mold . The manufacturing process of tempe reduces the cooking time and improves the digestibility and texture of many bowls of cereal/legume mixtures . The bacterium, i.e., Klebsiella pneumoniae (nonpathogenic strain), is responsible for producing vitamin B-12 when inoculated into Indian idli fermentation . Fermentation of the cactus plant (Agave) juices leads to Mexican pulque production and the oldest alcohol-containing beverage on America's continent . Pulque is very commonly consumed among low-income children of Mexico because of its richness in niacin, thiamine, pantothenic acid, riboflavin, and p-aminobenzoic acid biotin and pyridoxine . An alcoholic beverage, e.g., Kaffir beer, has a thin gruel consistency and pleasant sour taste [22]. Kaffir is a beverage traditionally prepared by the people of Bantu of South Africa with 1 to 8% alcohol content. Kaffir beverage was prepared from malted and unmalted kaffircorn (Sorghum caffrorum). The substitution for kaffircorn can be millet or maize. This alcoholic beverage increases riboflavin, and niacin/nicotinic acid nearly doubles, keeping the thiamin level constant during fermentation in people consuming maize . Palm sap is a sweet, plump, milky white suspension of bacteria and yeasts that is a colorless, transparent liquid containing approximately 10 to 12% fermentable sugar. It is consumed in the tropics. This type of wine consists of approximately 83 mg of ascorbic acid/L . In fermented palm wine, thiamine is increased from 25–150 μg/L, pyridoxine: 4–18 μg/L, and riboflavin: 35–50 μg/L. Surprisingly, there is a considerable amount of vitamin B-12 (190 to 280 μg/mL) in palm wine. Palm toddies are the cheapest vitamin B source and play a crucial role in nutrition economically drained in the tropics.

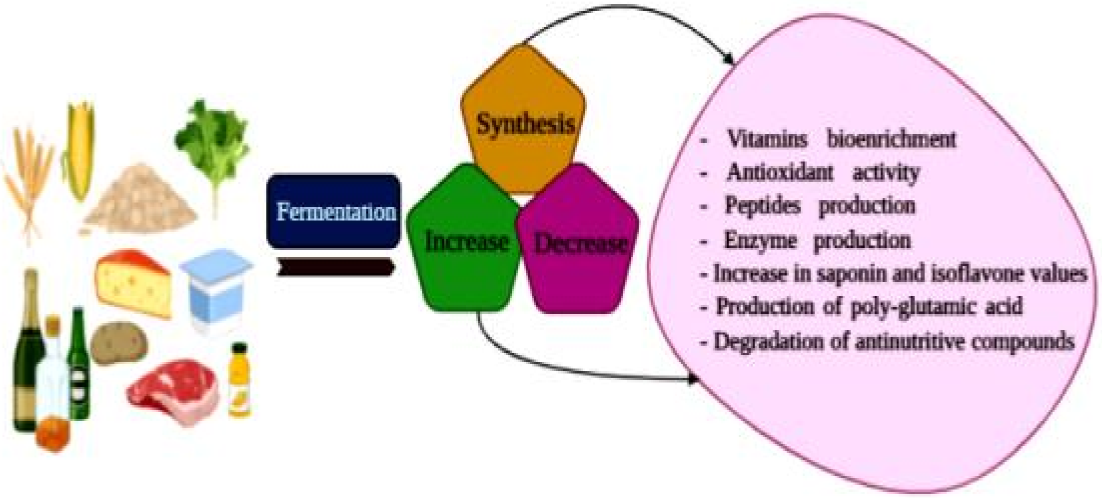


Figure 2. Nutritional enhancement in fermented foods. **Figure 2. Nutritional enhancement in fermented foods.**

Enzyme Production through Microorganisms

Enzymes such as amylase, proteinase, mannase, catalase, cellulose, etc. are generally produced from fermenting microorganisms, especially Bacillus, in Asian soya bean product fermentation of foods that hydrolyze complex substances into simple biomolecules (Table 2) . Carbohydrates-producing enzymes viz. like amyloglucosidase, α-amylase, maltase, pectinase, invertase, cellulase, alkaline proteases, lipase, and β-galactosidase are produced from mycelia fungi such as Amylomyces, Actinomucor, Aspergillus, Mucor, Monascus, Rhizopus and Neurospora in fermented foods/beverages . The enzyme produced by A. oryzae in koji, i.e., Taka-amylase A (T.A.A.), has numerous uses in industries . In the Himalayan region, stable, dry, and cake-like amylolytic starter cultures are used to produce alcohol. These starter cultures have mixed yeast strains such as Saccharomycopsis capsularis, S. fibuligera, and Pichia burtonii, increasing amylase . The enzyme nattokinase produced by B. subtilis present in natto has been observed for its fibrinolytic activity Other bacterial strains isolated from fermented foods like B. amyloliquefaciens, Vagococcus carniphilus, V. lutrae, P. acidilactici, Enterococcus faecalis, E. faecium, and E. gallinarum also shows fibrinolytic activity . The SK1-3-7 strain of Virgibacillus halodenitrificans isolated from fermented fish sauce [23] also showed fibrinolytic activity

Biochemical Changes During plant based Fermented food:

Fermentation in sourdough bread

There is a growing interest in grain-based products with excellent nutritional profiles and health-promoting properties. Sourdough bread is identified as one of the products that provide multiple health benefits to the consumer [24]. Sourdough is a mixture of water and flour, and it is fermented by cultures of indigenous yeasts and lactic acid bacteria. Additionally, bacterial species such as proteobacteria could be present at the beginning of fermentation . The microbial composition of the sourdough starter depends on the traditional practices used. Therefore, depending on the starter, the nutritional profile of the final product can be significantly different . Lactobacillus fermented, Lactobacillus paralimentarius, Lactobacillus plantarum, and Lactobacillus sanfranciscensis are the commonly found lactic acid bacterial species in sourdough. Typical sourdough yeast species are Candida humilis, Kazachstania exigua, and Saccharomyces cerevisiae . Lactobacillus sanfranscensisis is an obligate heterofermentative lactic acid bacteria 48 important for sourdough fermentation. It can produce a large amount of aliphatic amino acids, dicarboxylic amino acids, and hydroxyl amino acids, further improving product flavor. Lactobacillus sanfranscensisis the only lactic acid bacteria with a wide range of acidification and the same type of volatility in sourdough fermentation . Sourdough fermentation can improve food products' nutritional properties . During sourdough fermentation, yeast and LAB in the dough hydrolyze dietary fiber and increase the mineral bioavailability . Dietary fibers are one of the important bioactive compounds found in cereals, and the bioavailability of dietary fibers is influenced by technological functions taking place during processing . The composition of food dietary fibers and other bioactive compounds is influenced by baking and fermentation . It has been found that LAB strains can increase the content of functional compounds of whole grain flours both alone or in combination with in the baking process [25]. Sourdough fermentation can reduce the quantity of fermentable oligosaccharides, disaccharides, monosaccharides, and polyols (FODMAP) in the final product. Several studies have shown that fermentation could reduce at least 30% of the FODMAP, which results in sourdough bread with a lower amount of fermentable carbohydrates and free glucose . Moreover, it has been found that the level of FODMAP decrease in the fermented mass is inversely proportional to the fermentation time . Research studies on sourdough bread have found the inhibition of α-amylase compared to control bread, indicating less starch degradation . The digestibility of proteins increased in sourdough bread compared to yeast-leavened bread due to proteolysis during the fermentation period. Some authors have reported a 70-16 % increase in sourdough bread digestibility compared to bread made with baker's yeast (Saccharomyces cerevisiae E10) and an increased biological value of the protein[26]. In addition to nutritional improvements from sourdough fermentation, whole wheat flour is considered healthier than refined flour. Whole wheat flour contains higher levels of vitamins, minerals, dietary fiber (non-starch polysaccharides), antioxidants, and other phytochemicals such as carotenoids, flavonoids, and phenolic acids . Whole-grain flour can be obtained by either stone milling or roller milling. Recently, interest in using stone milling has grown due to the widespread opinion that stone-milled flours have a better nutritional profile than roller-milled flour [27].

Figure 3: Improvement of Sourdough and Bread Qualities by Fermented Water of Asian Pears and Assam Tea Leaves with Co-Cultures of Lactiplantibacillus plantarum and Saccharomyces cerevisiae

Physicochemical and Biological Properties of Fermented Plant Material

During fermentation, the plant matrix undergoes certain modifications. The physical properties of the plant material may change after fermentation and these changes may affect the biological and organoleptic properties of fermented food products. Initial characteristics of plant substrates used for fermentation may vary considerably in terms of their chemical composition and biological properties. This also influences the physiochemical and biological composition of the resulting product (Figure 1). The impact of the fermentation process on the plant matrix is dependent on the material and specific to the fermentation microorganisms. It is therefore possible to modify the final result by modifying the external environmental conditions of the process. Many product parameters can be controlled in order to obtain a product with attractive properties for the consumer. Not only the functional attributes but also such organoleptic features as the flavor, smell, and color are important. The pH value, fatty acid profile, mole solution, oxygen, humidity, duration of fermentation, remodeling of organic matter, color, texture, and rheological properties (e.g., consistency, stickiness, hardness, viscosity, and adhesiveness) are physicochemical properties that may change during fermentation. The changes are a result of biochemical processes occurring during fermentation and changes in oxygen and temperature. Changes in the physical properties of the product induced by fermentation influence the chemical and sensory characteristics of the fermented food [28]. These processes also have an impact on the biological properties and the population of bacteria present in the product, i.e., the number of bacteria and the composition of bacterial community may be altered.The pH value of a fermented product is an important factor closely related to the activity of microorganisms involved in fermentation. It contributes to microbiological stability against pathogenic and spoilage bacteria and is related to the flavor of the product. This was observed, e.g., in the analysis of a fermented camu-camu and soymilk combination. The reduction in the pH value was more rapid during fermentation carried out by L. plantarum than in the presence of Lactobacillus helveticus. This is related to the ability of particular bacterial strains to produce organic acids[29]. These compounds are generated in the process of decomposition of organic matter by microbes. The presence of organic acids, especially lactic acid, reduces the pH value to 5.0 or less [30]. The mechanism of this phenomenon is based on acid dissociation resulting in the release of hydrogen ions, which changes the balance of the solution and decreases the pH. For instance, it has been observed that fermentation of white beans by lactobacilli reduces the pH to 3.7–4.7 . L. plantarum CCMA 0744, L. fermentum CCMA 0745, and Lc. lactis CCMA 0415 used for yam (Dioscorea spp. L.) fermentation contributed to a decrease in pH from 6.1 to 3.7–3.8 through lactic acid production . Acidification of fermented soy beverages to pH 3.5 after 48-h fermentation by lactobacilli at 37 ◦C was observed . In the case of kimchi (fermented Chinese cabbage), the pH decreased from 5.34 observed in the early stage of fermentation to 4.30–4.40, which was maintained on the subsequent days of storage (7–67 days). This pH value was related to the presence of lactic and nitric acids[31]. Other authors have shown a decrease in pH from a value of 5.0–5.4 at the beginning of fermentation of kimchi to 4.0 after 57 days of fermentation [32]. In turn, the pH value during fermentation of pineapple increased from 3.4 to 4.0 for fruits fermented by W. cibaria and to 3.5 for those fermented by Ln. pseudomesenteroides, and the value remained constant after 16 days of storage. These changes may be caused by decarboxylation of citric or malic acid, which are present in pineapple[33]. Similar data were obtained after fermentation of prickly pear (Opuntia ficus-indica L.) fruit puree by LAB. The pH value decreased to approx. 3.92–4.10 during storage and further to ca. 3.72–3.78 after 21 days, which was connected with the production of lactic and acetic acids by the bacteria[34]. A low pH not only results from the presence of microorganisms but also affects their community. At a low pH, lactic acid bacteria begin to dominate in the product. In the later phase of fermentation of plant material in acidic conditions, organic acids and protein are decomposed, resulting in release of carbonic acid, ammonia, and a small amount of N2, CO2, and CH4, thus increasing the pH value again. The growth of microorganisms during fermentation is also closely related to temperature. The activity of microorganisms in the fermented product contributes to an increase in the temperature of the plant material, since energy is generated in the form of heat, CO2, and water vapor during the decomposition of organic matter. After reaching a maximum value, the temperature during fermentation begins to decrease, possibly as a result of the activity of microorganisms contributing to the reduction in the nitrogen content of the material as they break down organic matter into simpler compounds. Nitrogen and organic material are used by microorganisms for their activity and development; therefore, a decrease in their content reduces the number of microorganisms in the product [35]. The structure of microbial communities is an important factor influencing the fermentation process. The initiation and progression of fermentation depends on the bacterial microbiota. Bacterial growth during fermentation has been shown to vary depending on the components of the plant material, storage method and temperature, salinity of the product, etc. The type of plant material can promote the growth of certain bacteria during fermentation. This was demonstrated by Fujita et al. in a study on a fermented product containing a combination of soymilk with camu-camu powder. Both L. plantarum and L. helveticus were able to grow successfully in this plant material, but L. helveticus had better performance of growth and stability during fermentation. This was apparently related to the high protein content in soymilk, which contributed to the growth of L. helveticus, a known protease producer[36]. Fermented soy was found to support the growth of BB-12®® Bifidobacterium. Furthermore, the viability of this strain was demonstrated in soy desserts.

Mechanism:

During fermentation, microbial activity changes the chemical composition of the fermented plant material . Bacterium-specific metabolic features combined with plant enzyme activity can improve the bioavailability of certain phytochemicals . Raw material components are enzymatically and chemically decomposed and subsequently modified in biotransformation reactions . Bacteria are capable of converting substances contained in plant substrates into a variety of compounds, which can lead to a marked increase in the amount of functional microbial metabolites, often exhibiting valuable nutritional properties . Changes in the chemical composition of plant material are mainly caused by decomposition by bacterial enzymes. Various studies have shown alterations in bacterial enzyme activity during fermentation. They were observed, e.g., during fermentation of a camu-camu and soymilk combination by LAB strains. The results showed higher inhibitory activity of α-amylase and α-glucosidase. Furthermore, α-galactosidase activity has been demonstrated in soybeans fermented by the BB-12®® Bifidobacterium strain. Its presence may reduce the galactooligosaccharide content of soymilk, which is important because these molecules cannot be digested in the human intestine [37]. Phytase is another beneficial enzyme produced by bacteria in fermented plant products. It is responsible for decomposition of phytate, which is an anti-nutritional compound. Its presence was demonstrated in, e.g., fermented quinoa sourdough. The phytase activity in this product was around 2.75-times higher than that in raw quinoa flour . Fermentation of sourdough made from legume or pseudocereal flour reduced the phytate content in the final product due to the activity of cereal phytase supported by the low pH value resulting from the activity of microorganisms . Phytase was detected in yams fermented with Lc. lactis CCMA 0415. The fermentation of yams by this strain resulted in 82% reduction in the phytate content. This bacterium also produces α-amylase during yam fermentation. The activity of this enzyme results in degradation of starch contained in the plant material to fermentable carbohydrates, which are then used by the bacteria to produce, e.g., organic acids . Lactobacilli also produce fatty acid hydratase and are thus capable of converting polyunsaturated fatty acids to hydroxyl and conjugated fatty acids, which are known bioactive compounds. Linoleic isomerase activity, in turn, is related to the presence of L. plantarum in the fermented substrate. As a result, fermentation of certain plant materials (e.g., sunflower and castor oil or nuts) by this bacterial species results in enrichment of the product with conjugated linoleic acid . It has been shown that, during cocoa fermentation, lactic acid bacteria can produce citrate lyase; however, its activity is strongly influenced by environmental conditions (pH, temperature). A consequence of the activity of this enzyme in the early stage of cocoa bean fermentation is the decomposition of citric acid by the bacteria to produce acetic and lactic acid . In another study, Filannino et al. reported that the action of bacterial glycosyl hydrolases during lactic fermentation of cactus cladode pulp resulted in the release of two flavonoid aglycones (isorhamnetin and kaempferol) with antioxidant activities . The increase in the phenolic content in products fermented by LAB is presumably associated with the action of enzymes that cause depolymerization or hydrolysis of phenolic compounds. Several enzymes, e.g., tannase and β-glucosidase (detected in Ln. mesenteroides, Weisella paramesenteroides, and Ln. fallax) or feruloyl esterase (observed in Leuconostoc spp.) can be involved in these reactions, inducing changes in the plant matrix, e.g., during fermentation of fruit juices . Phenolic compounds can also be formed during fermentation as a result of tannin degradation, as Foods 2021, 10, 1603 11 of 22 demonstrated for fermented quinoa sourdough. The activity of such enzymes as oxygenases and decarboxylases or other LAB and quinoa endogenous enzymes may be involved in the degradation of tannins . Fermentation of quinoa flour by lactic acid bacteria was also shown to cause proteolysis of native quinoa proteins, resulting in the release of antioxidant peptides [38]. Thus, a number of transformations take place in plant material fermented by bacteria. These include conversion of the chemical constituents of the plant matrix, resulting from the activity of enzymes of bacterial origin. The chemical composition of the plant matrix determines not only the physicochemical properties of the final product but also the range of microorganisms that will be able to grow in the material and carry out the fermentation process.

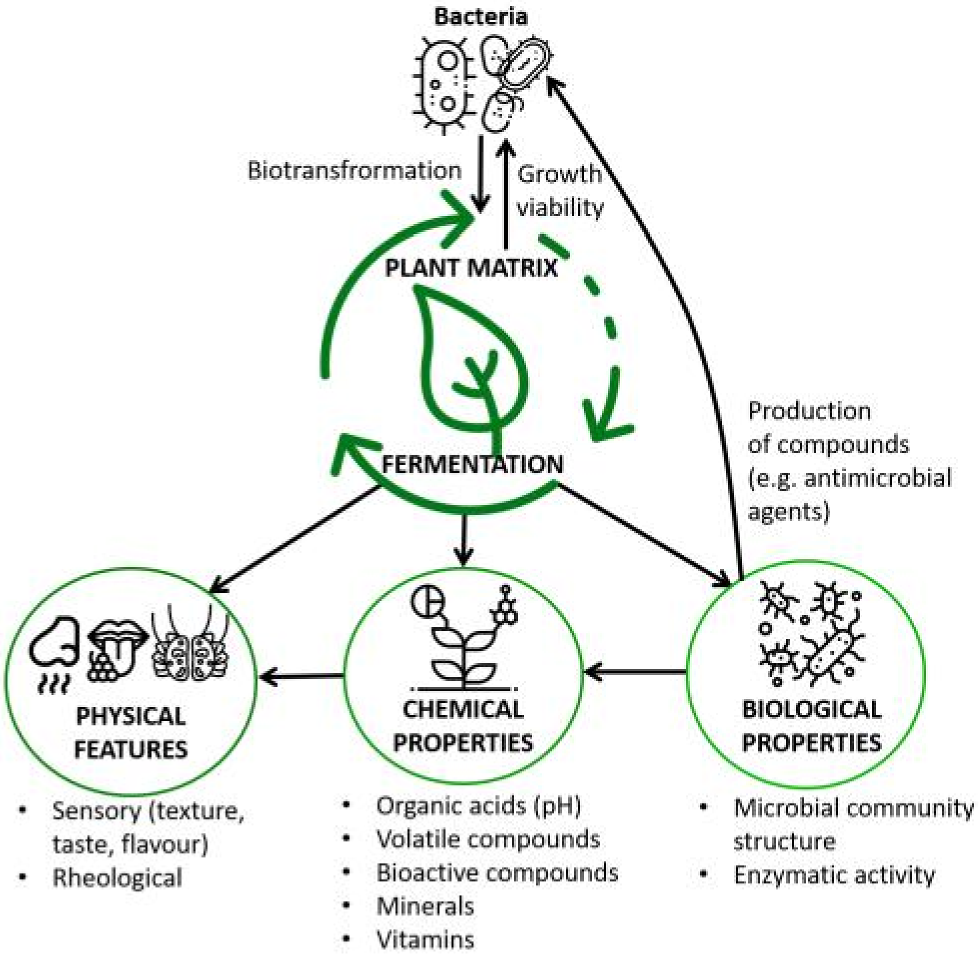
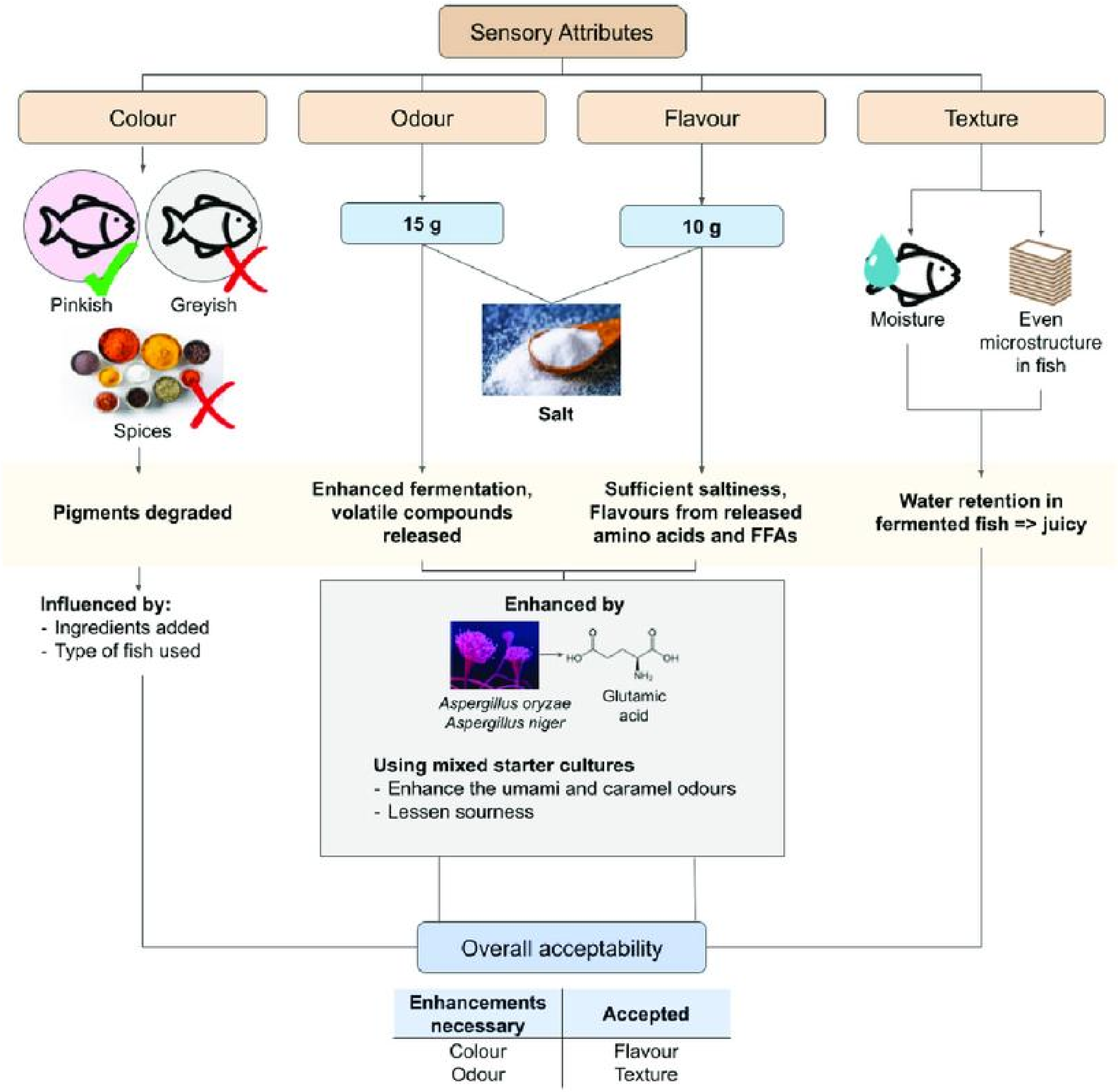


Figure 4: Fermentation as a determinant of the physical, chemical, and biological properties of plant material

Sensory properties of fermented food:

In addition to its impact on the sensory properties of food, fermentation can significantly improve the nutritional value of food by introducing new pathways that produce vitamins and micronutrients. This is particularly important for vulnerable groups who may have limited food choices. Fermentation can also increase food functionality by releasing or synthesizing bioactive compounds with functional potential, such as bacteriocins, or providing probiotics and postbiotics. For instance, the fermentation of soybean with *Enterococcus faecium* contributed to flavor development but also the inhibition of *Lysteria monocytogenes* through a bacteriocin produced during fermentation instead, evaluated the prebiotic effect of red ginseng dietary fiber on a *Lactiplantibacillus plantarum* strain. Red ginseng dietary fiber supplementation promoted the probiotic properties of *L. plantarum*, including the production of short chain fatty acids, carbohydrate utilization, attachment to intestinal epithelial cells, and pathogen inhibition.Improvements with proteins and microbial fermentation are currently in the process of making novel foods a global commercial success. For instance, recent progress in plant-based foods has focused on producing proteins that may lead to umami flavors and precursors that are transformed into savory compounds during the cooking process. The investigation of efficient and cost-effective alternative protein sources is also a topic of interest explored by [39]. The researchers focused on distillers' dried grains, a co-product of bioethanol production, which are rich in protein. They used an integrated approach that included analyzing the genome of *Paenibacillus pabuli*, assessing *in vitro* enzymatic activities, and conducting solid-state fermentation to assess the suitability of the strain to degrade non-starch polysaccharides.



Enhancements necessary	Accepted
Colour	Flavour
Odour	Texture

Figure 5: summary of sensory attributes

Health benefits and functional properties of fermented food:

Microbial biotransformation, a term encompassing both fermentation and broader microbial metabolic processes, is a key driver in this revolution. This refers to the process by which microorganisms chemically modify food components through their metabolic activities, leading to the formation of new compounds or the enhancement of existing compounds. Microbial biotransformation plays a pivotal role in the production and improvement of a wide range of food products, particularly fermented food products[40] . By employing various beneficial species of bacteria, yeasts, and fungi, microbial biotransformation through fermentation can significantly alter the nutritional and sensory properties of food, thereby enhancing its value and functionality . The significance of microbial biotransformation extends beyond food production; it is central to the complex interplay between diet, microbiota, and human health and has garnered considerable interest in recent years.Through fermentation, a core aspect of this process, beneficial microorganisms transform raw food substrates into products with enhanced nutrient bioavailability and functional properties. This capability to convert basic food components such as milk, cereals, vegetables, legumes, and meat into a diverse array of fermented products underscores the profound impact of microbial biotransformation on human nutrition and health. Figure 1 provides a comprehensive overview of how diverse food substrates, including milk, cereals, vegetables, legumes, fruits, meat, and fish, undergo beneficial microbefacilitated fermentation, resulting in their transformation into nutritious products that have a positive impact on human health. This age-old practice has been indispensable not only for food processing and preservation but also for enriching the nutritional value of foods, resulting in a diverse range of fermented products that are still staples in many cultures and offering significant health benefits. Fermentation 2025, 11, x FOR PEER REVIEW 2 of 30 Microbial biotransformation, a term encompassing both fermentation and broader microbial metabolic processes, is a key driver in this revolution. This refers to the process by which microorganisms chemically modify food components through their metabolic activities, leading to the formation of new compounds or the enhancement of existing compounds. Microbial biotransformation plays a pivotal role in the production and improvement of a wide range of food products, particularly fermented food products . 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Although fermentation remains the cornerstone of microbial biotransformation and has been utilized for centuries as a natural method of food preservation and flavor enhancement [41], the potential of microbial biotransformation extends far beyond traditional practices. Modern advances in microbiology and biotechnology have revealed the extensive capability of microorganisms to synthesize bioactive compounds, reduce anti-nutritional factors, and improve the bioavailability of essential nutrients . These transformations are driven by the enzymatic machinery of microorganisms, which catalyzes a variety of biochemical reactions, leading to the modification of carbohydrates, proteins, lipids, and other food constituents.In recent years, the evolution of microbial capabilities has led to significant shifts in the global food industry and consumer preferences. There is an increasing demand for foods that not only satisfy basic nutritional needs but also contribute to overall health and well-being [42]. This shift has fueled a growing interest in the development of functional foods that offer additional health benefits beyond their inherent nutritional value. As a result, enhancing the nutritional properties and functional benefits of food has become crucial, particularly in addressing public health challenges and improving the quality of life. One of the primary drivers for enhancing nutritional properties is the need to combat various forms of malnutrition, including micronutrient deficiencies, that affect millions of people worldwide [43].

Microbial biotransformation plays a crucial role in this process by improving the bioavailability and concentration of essential nutrients, such as vitamins, minerals, and amino acids, in food products. For example, through fermentation, microorganisms can increase the levels of B-vitamins or convert precursors into bioactive forms of nutrients, making them more readily absorbed by the human body . In addition to addressing nutritional deficiencies, enhancing the functional benefits of foods through microbial biotransformation has significant potential for disease prevention and health promotion. For example, foods enriched with probiotics have been shown to improve gut health, boost the immune system, and reduce the risk of chronic diseases [44]. Similarly, the synthesis of bioactive compounds such as antioxidants, peptides, and polyphenols during microbial fermentation can contribute to the prevention of oxidative stress, inflammation, and other conditions associated with aging and lifestyle diseases[45] . Furthermore, the enhancement of functional properties also encompasses the improvement of sensory attributes such as taste, texture, and aroma, which are critical to consumer acceptance. Foods that are both nutritious and appealing are more likely to be incorporated into regular diets, thereby maximizing their health benefits [46]. The development of novel flavors and textures through microbial biotransformation not only increases the diversity of food choices but also supports cultural and culinary innovation. As the field of food science continues to evolve in response to growing consumer demand for healthier and more sustainable options, understanding the intricate mechanisms by which microorganisms transform food components is essential for advancing both academic knowledge and industrial applications. This review aims to consolidate the current knowledge in the field, highlight key developments, and identify emerging trends that could shape the future of functional food production.[47] By covering these areas, this review aims to provide a holistic understanding of microbial biotransformation and its potential to revolutionize the food industry[48]. This review aims to bridge the gap between traditional fermentation practices and modern biotechnological approaches by providing a detailed analysis of how microbial biotransformation can be harnessed to improve food quality and health outcomes. In addition to these core objectives, this review discusses the challenges in scaling up microbial biotransformation for industrial applications, ensuring quality control, and gaining consumer acceptance. It also explores future directions and innovations in the field, particularly in the context of sustainable food production and the potential for waste reduction. In addition, this review aims to provide a valuable resource for researchers, food industry professionals, and policymakers by offering insights into how microbial biotransformation can be leveraged to create nutritionally enhanced and functionally superior food products. By synthesizing the current knowledge and identifying areas for future research, this review will contribute to ongoing efforts to improve global food security and public health.[49]

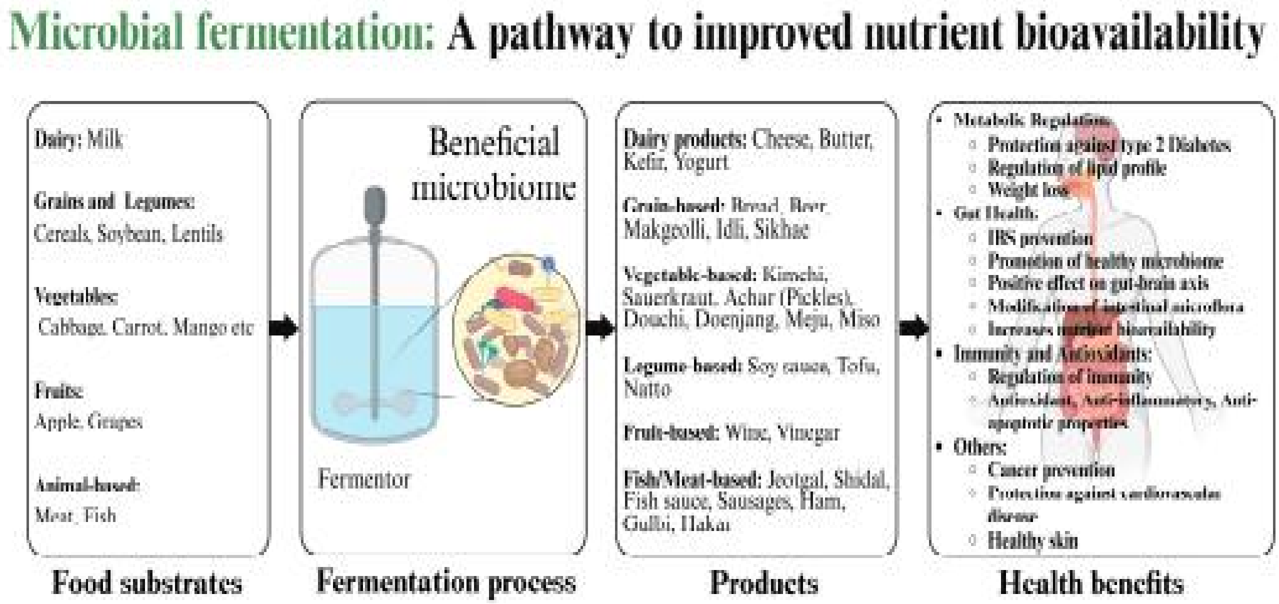

Figure 6: Microbial fermentation in food: a comprehensive overview of the fermentation process, substrates, products, and associated health benefits [50].

Challenges and limitations:

Plant-based fermented foods hold great promise for improved nutrition and health benefits, yet their development is challenged by complex microbiological, biochemical, and sensory limitations. On the microbiological front, ensuring consistent and safe fermentation remains problematic, as traditional spontaneous processes often lead to variable microbial communities, which in turn may result in unpredictable product quality and potential safety risks, including the transfer of undesirable traits such as antimicrobial resistance. Biochemically, the inherent variability in plant substrates—ranging from differences in protein, carbohydrate, and fat composition to the presence of anti-nutritional factors—complicates the fermentation process; uncontrolled enzymatic activities can lead to both the loss of vital nutrients and the formation of unwanted metabolites, thereby impairing the nutritional and functional profiles of the final products. Additionally, the sensory attributes of plant-based fermented foods, such as flavor, texture, and appearance, are frequently inconsistent, with challenges including residual off-flavors (e.g., beany or bitter notes), undesirable textural changes (e.g., sliminess or insufficient fibrous structure), and unstable color profiles that do not match traditional animal-based products. Addressing these interconnected challenges requires the development of optimized starter cultures, refined control of fermentation parameters, and integration of innovative processing technologies to produce plant-based fermented foods that are nutritionally robust and consistently appealing to consumers.

Future prospective:

Researchers are expected to develop and optimize robust starter cultures, tailored specifically to the unique composition of plant matrices, which will help ensure consistent fermentation outcomes while minimizing risks associated with contamination and undesirable microbial traits. Advances in omics technologies and artificial intelligence will likely play a critical role in unraveling the complex interactions between plant substrates and fermentative microbes, allowing for precise control over enzymatic reactions and the production of bioactive compounds. Furthermore, innovative processing techniques—such as nonthermal preservation methods and integrated fermentation systems—are anticipated to enhance the retention of nutritional and sensory qualities, leading to products with improved flavor profiles, desirable textures, and stable appearance. Overall, interdisciplinary collaboration between microbiologists, food technologists, and sensory scientists is expected to transform plant-based fermented foods into reliable, health-promoting, and consumer-acceptable alternatives that can meet the growing demands of a sustainable food system.

Conclusion:

plant-based fermented foods offer significant promise as health-enhancing, sustainable alternatives to traditional animal-derived products, they are not without considerable challenges. The complex interplay of diverse plant substrates and fermentative microorganisms creates variability that can compromise safety, nutritional consistency, and sensory quality. Uncontrolled microbial activity may lead to inconsistent flavor profiles, unwanted texture alterations, and unstable color attributes, all of which can hinder consumer acceptance. Moreover, the inherent biochemical diversity of plant materials poses additional hurdles in optimizing fermentation processes to maximize the release of bioactive compounds while preventing nutrient loss and the formation of off-flavor metabolites. Addressing these limitations will require an integrated, multidisciplinary approach that combines advances in microbial biotechnology, process engineering, and sensory science. By refining starter culture formulations, implementing precise control of fermentation parameters, and adopting innovative processing techniques, future research holds the potential to transform these challenges into opportunities, ultimately enabling the consistent production of high-quality, nutritionally robust, and appealing plant-based fermented foods.

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