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Review

From Ancient Fermentation to Modern Functional Foods: Food Microbiology and Biotechnology at the Interface of Tradition and Innovation

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Abstract

Fermentation is one of the oldest food preservation and transformation strategies developed by human societies. Its cultural appropriation predates even the scientific understanding of the role of microorganisms and their metabolic functions. However, significant knowledge gaps remain regarding the mechanisms underlying these effects, as well as safety considerations and regulatory frameworks. This review addresses these gaps through an integrative analysis of the literature, including peer-reviewed studies and systematic reviews focused on food microbiology, microbial dynamics, and health-promoting mechanisms. In particular, yogurt and cheese are addressed as case studies to review the past and present of these ancestral foods in terms of the evolution of fermentation processes, from spontaneous fermentation to controlled and standardized systems, along with the modern biotechnological tools used to characterize and monitor complex microbial communities. Substrates such as stevia, fruits, vegetables, and plant-based milk substitutes are also explored. The scope encompasses enzymatic transformation of raw substrates, biosynthesis of bioactive metabolites, effects on the gut microbiota, and the use of fermented foods as vehicles for "biotic" compounds. Particular attention is paid to safety and regulatory aspects. Fermented foods are culturally important and promising functional platforms, although standardized regulatory frameworks and stronger mechanistic and clinical evidence regarding their health benefits are still needed.

Keywords: traditional fermentation; microbial metabolism; food biotechnology; functional foods; gut microbiota; food safety; technological innovation

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1. Introduction

Food is an integral component of human civilization, shaping not only nutrition but also culture, traditions, and social identity. A profound transformation in the way people eat has occurred due to urbanization and globalization, despite changes in dietary patterns [1]. The domination of ultra-processed foods rich in saturated fats, simple sugars, emulsifiers, and chemical additives has been observed in modern diets and is showing an ongoing increase. Disruptions in the gut microbiota, with long-term health consequences, have occurred from the widespread use of antibiotics and proton pump inhibitors. However, traditional dietary practices may help restore balance and support health.

Fermented foods are one of the oldest and most enduring components of the human diet. An enhancement of food safety and extension of shelf life constitute some of the major advantages of fermentation, playing a crucial role in the survival of early human populations [2,3]. Products obtained through controlled microbial growth and the enzymatic transformation of food components could be defined as fermented foods [4]. Fermentation, being a natural preservation strategy, reduces the risk of contamination while simultaneously generating distinctive flavors and textures that differentiate fermented foods from their raw substrates; this occurs through the production of organic acids, ethanol, and bacteriocins [1].

Fermented foods show remarkable diversity, reflecting the wide range of food–microbe interactions developed across cultures, with thousands of products being consumed globally [5,6]. The industrialization of food systems in Western societies over the past century has led to a decrease in the diversity and consumption of traditionally fermented foods, despite their historical ubiquity and cultural significance. A shift toward artisanal production methods and an increasing awareness of the health-promoting potential of these foods has been detected over the last few years [7–9].

Advances in food microbiology and biotechnology unravel the complex mechanisms underlying the functional properties of fermented foods. Fermentation can also modulate the nutritional profile of foods, affect bioactive compound formation, and contribute beneficial microorganisms that may interact with the host, showing benefits beyond preservation and sensory enhancement [10–12]. Hence, an interaction between ancient practices and modern science has been shown for fermented foods, offering a combination of traditional knowledge with innovative approaches towards improvements in diet and health.

This review addresses these gaps through an integrative analysis of the literature, including peer-reviewed studies and systematic reviews focused on food microbiology, microbial dynamics, and health-promoting mechanisms. In particular, yogurt and cheese are addressed as case studies to review the past and present of these ancestral foods in terms of the evolution of fermentation processes, from spontaneous fermentation to controlled and standardized systems, along with the modern biotechnological tools used to characterize and monitor complex microbial communities. Substrates such as stevia, fruits, vegetables, and plant-based milk substitutes are also explored. The scope encompasses enzymatic transformation of raw substrates, biosynthesis of bioactive metabolites, effects on the gut microbiota, and the use of fermented foods as vehicles for "biotic" compounds. Particular attention is paid to the safety and regulatory aspects. Fermented foods are culturally important and promising functional platforms, although standardized regulatory frameworks and stronger mechanistic and clinical evidence regarding their health benefits are still needed.

This article offers a broad and integrative perspective by placing fermented foods at the intersection of cultural heritage and modern biotechnological innovation. Its contribution lies in synthesizing ancestral knowledge with contemporary advances in food microbiology. Furthermore, the review not only highlights the scientific mechanisms underlying the health-promoting potential of fermented foods but also contextualizes them within food systems, consumption trends, and the challenges of global sustainability. This approach provides a more comprehensive understanding of fermented foods, both as cultural products and as innovative functional foods relevant to modern public health and future food security.

This is a narrative review that offers an integrated synthesis of the literature of the last 30 years as well as the most relevant previous publications. The literature search was conducted in major scientific databases, including PubMed, Scopus, Web of Science, and Google Scholar, among others. Keywords used for the search included: "fermented foods", "traditional fermented foods", "history of fermentation", "functional foods", "probiotics", "next-generation probiotics," and "prebiotics," among others. Peer-reviewed articles, reviews, and authoritative reports published exclusively in English were considered. Studies were included based on their relevance to the microbiological, biotechnological, nutritional, functional, and safety aspects of fermented foods, as well as their contribution to the understanding of the relationship between traditional fermentation practices and modern scientific advances.

2. Defining Fermented Foods: Microbial Processes, Substrates, and Conceptual Boundaries

Foods or beverages produced through the intentional activity of microorganisms, which drive the enzymatic transformations of both major and minor components within the raw materials, are named fermented foods. Significant biochemical changes that shape the safety, sensory qualities, and nutritional profile of the final product arise from this controlled microbial growth [4]. However, many traditional fermented foods are produced by spontaneous fermentation or back-slopping, starter-culture fermentation, and controlled industrial fermentation [13–15].

The classification of fermentation processes is carried out according to the dominant metabolites produced and the microorganisms involved. Ethanol and carbon dioxide production comes from yeasts, whereas acetic acid comes from acetic acid bacteria (e.g., *Acetobacter* spp.). Lactic acid is produced by lactic acid bacteria (LAB), including genera such as *Leuconostoc*, *Lactobacillus*, and *Streptococcus*, whereas *Propionibacterium freudenreichii* is responsible for propionic acid fermentation [16,17]. The production of ammonia and fatty acids is associated with *Bacillus* species and certain molds. The categorization of fermentations may be carried out based on the substrate used, encompassing meat and fish, dairy products, vegetables, legumes (including soybeans), cereals, starchy roots, and fruits [5].

Importantly, fermented foods are largely associated with microbial activity during production rather than the presence of viable microorganisms in the final product. As Marco et al. [4] reported, fermented foods are still classified as fermented even if subsequent processing steps inactivate or remove the microorganisms. For example leavened bread is baked with heat eliminating fermenting yeasts, and beer and wine are beverages that may be filtered or pasteurized prior to consumption. However, in these cases, fermentation contributes to the development of the product's characteristics.

On the other hand, products that merely contain fermented ingredients—such as condiments made with vinegar or dairy-based additives—are not fermented themselves and do not meet the criteria to be considered as fermented foods [4]. Similarly, when microorganisms are added to foods without an active fermentation process, or are the product of non-microbial enzymatic processes, these are also not considered fermented. Acidified cheeses, black tea, Southeast Asian fish sauces, non-microbial pickled vegetables, synthetic vinegar, industrially manufactured soy sauce, and certain cured meats produced solely through chemical additives (e.g., nitrate or nitrite salts) are not considered fermented [4,18]. However, fish sauce and soy sauce are generally recognized as fermented products when produced through microbial or enzymatic fermentation [19,20].

Hence, despite the nutrient-rich and microbiologically dynamic foods arising from traditional fermentation practices, the trend shows a broader shift toward the large-scale production of ultra-processed foods.

3. Globalization of Fermented Foods and the Challenge of Preserving Quality, Identity, and Microbial Biodiversity

At present, more than 5000 varieties of fermented foods (and beverages) are produced and consumed worldwide [4], despite the increase in the consumption of fast food, ultra-processed foods and foods with chemical additives leading to changes in our nutritional habits.

Fermented products are significant in modern diets, constituting almost a third of global food consumption [21]. The main fermented foods consumed around the world are shown in Figure 1. In Asia, the Korean diet includes fermented vegetable products such as kimchi, describing a dish of fermented vegetables such as cabbage, radish, and cucumber. Currently, there are over 200 varieties in Korea [6]. The activity of LAB, present in raw materials, produces a large quantity of organic acids and other compounds that contribute to its unique and complex flavor, causing spontaneous fermentation. Moreover, the use of starter cultures has been incorporated into the industrial and standardized production of kimchi [22].

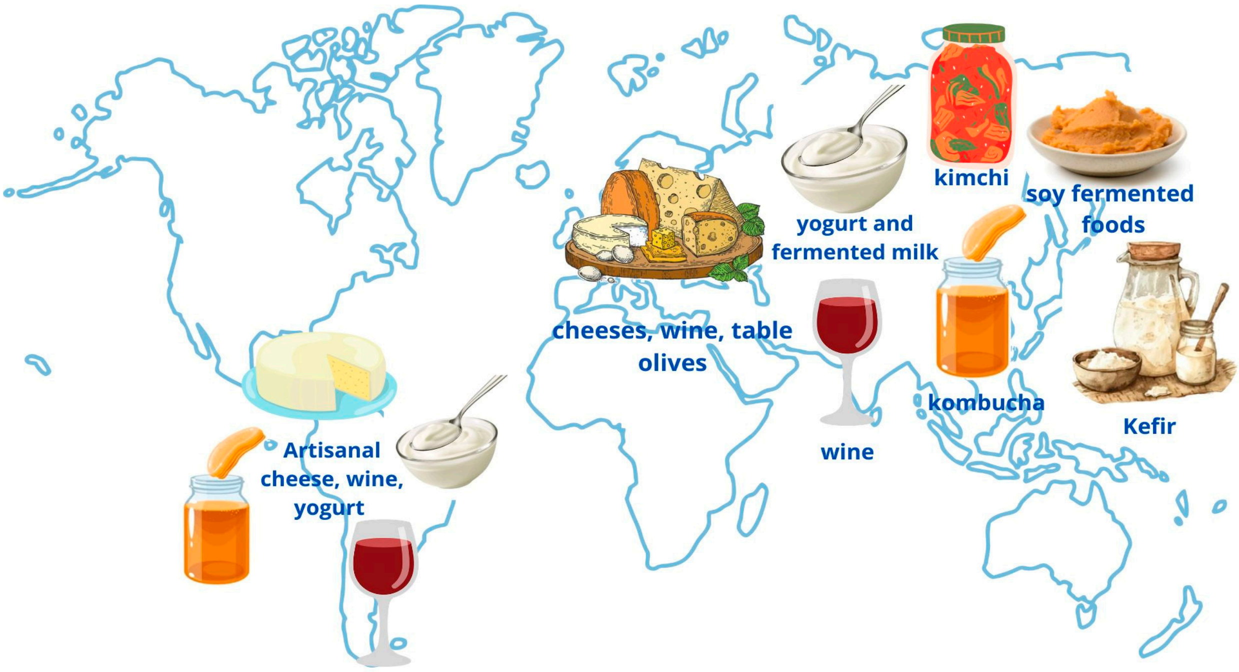

Figure 1. Representative fermented foods worldwide.

Fermented soybean foods such as soy sauce, miso and tempeh are widespread across East and Southeast Asia (the latter in Indonesia). Complex microbial processes involving molds, yeasts, and LAB generate characteristic flavors and textures while enhancing protein digestibility and bioactive compound formation; these are responsible for the production of these products [23].

The activity of a complex consortium of bacteria and yeasts contained in kefir grains [24] produces kefir, a fermented milk beverage originating in the Caucasus region. Similarly, the consumption of kombucha, a fermented tea produced by a symbiotic culture of bacteria and yeast (SCOBY) in parts of East Asia, has recently gained global popularity (growth of approximately 30% annually) due to perceived health benefits [24].

In Latin America, the kombucha market was valued at USD 112.75 million in 2022 and is expected to triple by 2027 [25]. A wide range of cereal-based beverages and fermented dairy products that remain important in local food systems in Latin America constitute fermentation traditions. Meanwhile, in Europe, particularly in the Mediterranean regions, key components of both traditional diets and agricultural economies are fermented foods such as cheeses, wine, table olives, cured meats, and pickled vegetables [5].

Fermented foods represent dynamic microbial ecosystems that link traditional knowledge with modern research on microbiomes, nutrition, and food biotechnology beyond their gastronomic and economic importance.

However, the large-scale industrial production of fermented foods needs to ensure safety, product quality and process control, microbiological stability, and standardized manufacturing processes, and consistency, and thus requires replacement by commercial starter cultures [26]. This poses a threat not only to microbial diversity but also to the biocultural diversity of food production and the distinctive sensory characteristics associated with traditional fermentation [27].

Hence, the potential consequences of microbial loss for human health have recently been highlighted [28,29]. The results of the interaction between the genetic structure encoded in the human genome and its long-standing coexistence with vast communities of microorganisms throughout evolutionary history are clear in the human body. These associated microorganisms collectively constitute the human microbiota [30]. The preservation of microbial diversity is therefore considered essential for the maintenance of health and the prevention of a wide range of metabolic, immune, and cognitive disorders [31]. Thus, interest in fermentation practices has grown recently, as shown by the growing attention to the consumption of probiotics, prebiotics and postbiotics as strategies to restore and maintain microbiota diversity.

4. Yogurt and Cheese as a Case Study: Past and Present of Two Ancestral Fermented Foods

Yogurt and cheese are among the oldest and most widely consumed fermented dairy products, having emerged thousands of years ago, illustrating the historical role of microbial fermentation in food preservation, cultural identity, and human nutrition. Fermentation has long been used to preserve milk and enhance its nutritional and sensory properties [32,33]. Table 1 shows traditional and emerging fermented foods, their associated microorganisms, bioactive metabolites, and their functional properties.

Fermented dairy products are generally traced back to regions of the Near East and Central Asia approximately 8000–10,000 years ago. In these pastoral systems, the domestication of goats and sheep by the communities first took place, followed by cattle. However, milk was highly perishable, and spontaneous fermentation took place to extend its shelf life [34]. The activity of naturally occurring LAB fermentation transformed lactose into lactic acid, lowering the pH and stabilizing the product, which led to yogurt production (Figure 2). Back-slopping techniques were used in traditional yogurt production, where a portion of a previous batch served as a starter culture for the next fermentation cycle [27]. A complementary strategy to concentrate and preserve milk nutrients is cheese production. Curdling milk using natural enzymes such as rennet, followed by the separation of curds and whey and subsequent fermentation and aging, was the process of so-called early cheesemaking [32]. Regional practices, over time, generated an extraordinary diversity of cheeses, reflecting differences in milk sources, microbial communities, environmental conditions, and artisanal techniques.

Industrial-scale manufacturing of yogurt and cheese took place during the twentieth century with standardized starter cultures, controlled fermentation conditions, and large-scale processing to improve product consistency, safety, and distribution (Figure 2) This led to reduced microbial diversity and, often, the replacement of traditional fermentation ecosystems with simplified industrial cultures. Moreover, the incorporation of stabilizers, flavorings, and other additives in commercial dairy-based foods prioritizes shelf stability and mass production over traditional fermentation practices.

LAB present several key technology processing characteristics essential for dairy production, such as acidification (lowering pH and inhibiting pathogens) [35], proteolysis (peptides and amino acids' formation following the breakdown of proteins to improve texture and flavor), lipolytic or esterolytic activities (the modification of lipids for aroma compounds generation), and organic acid and bacteriocin production to antagonize spoilage and pathogenic bacteria [36–38] (Table 1). Resistance to various stressors, such as high salt concentrations, bile salts, and low pH, which are essential for survival and functionality in the gastrointestinal tract and during food processing, is exhibited by LAB [39]. LAB, as biopreservatives, enhance the safety and quality of traditional fermented products, bringing sustainability to food systems by reducing the reliance on synthetic additives [40]. They also help in the maintenance of gut microbiota [41] and lead to improvements in the bioavailability of vitamins, amino acids and minerals [42].

The biopreservative properties of LAB isolated from 167 dairy samples across 11 regions of Morocco, and related technologies, were investigated by Gardoul et al. (2026) [43] with the most potent antibacterial activity identified in isolates of *Enterococcus faecium*, *Lactiplantibacillus plantarum*, and *Lactococcus lactis*.

4.1. The Case of Yogurt

The transformation of milk into yogurt requires the effect of a starter culture—known as maya in Turkish, denoting 'essence' or 'substance' [27]. Yogurt is defined as a fermented dairy product containing viable symbiotic bacterial cultures, such as *Streptococcus thermophilus* and *Lactobacillus delbrueckii* subsp. *bulgaricus*. These bacteria are responsible for the development of characteristic flavors along with rapid acidification. Fermentation also modulates the nutritional content and sensory properties of milk, particularly its texture [43] (Table 1). Natural additives have also been added in yogurt as reported by Bankole et al. [44].

Traditional yogurt production, in Bulgaria, Turkey or other countries, involves products with high microbial diversity. Seventy-six strains of LAB [45] were identified in Bulgarian homemade yogurts, suggesting the evolution of starter cultures with unique profiles, arising from regional microbial ecosystems and local environmental and climatic conditions.

Sirakova (2023) [27], in an ethnobiological study, highlighted the biocultural diversity of ancestral yogurt-making practices from Bulgaria and Turkey. Microorganisms originate from the milk itself, the environment, the air, rainfall, or the storage vessels in these traditional fermentations. At present, for instance, there exist soil- and root-associated microbes that likely play a significant role in fermentation. Moreover, yogurt could be produced by mixing nettle roots with milk. The use of ants as a 'starter' has also been described by Sirakova (2023) [27]. The synergistic effect of ant-derived acids and the microorganisms within ant colonies could create favorable conditions for fermentative bacteria [46,47]. Furthermore, ant-associated bacterial communities contribute lactic and acetic acids, while the ants themselves provide formic acid, as reported by Sinotte (2025) [33]. In this way, acidification and coagulation are facilitated. Additionally, both ants and bacteria produce casein-active proteases, contributing significantly to the yogurt's final texture.

Health functionalities have become decisive factors in product selection following the growth of functional foods and wide consumer interest [9]. The production of probiotic, prebiotic, and synbiotic yogurts designed to support gastrointestinal health has risen during the last decade [48–50]. Plant-based products—derived from fruits, vegetables, grains, and seeds—and specialized dairy options like lactose-free or A2 milk formulations, which offer enhanced digestibility for sensitive populations, constitute diverse, innovative raw materials [51–53].

Diverse protein sources for yogurt and cheese enrichment mimic dairy structures and focus on plant-based proteins (PBPs) such as soy, pea, and oat [54]. These globular proteins form stable networks resembling traditional dairy matrices while providing beneficial fibers and antioxidants when they are denatured [55]. However, significant technical and sensory hurdles have been found with these PBPs, including off-flavors triggered by lipoxygenase activity and inferior mechanical properties that necessitate the use of exogenous stabilizers and emulsifiers [56]. Furthermore, lower nutritional density and lower conversion efficiency compared to bovine milk [57] are some of their disadvantages. Advanced alternatives include single-cell proteins—biomass derived from algae, bacteria, and yeast—offering a highly sustainable and nutrient-dense replacement that can be purified for human consumption [58]. Recombinant dairy proteins are another option, produced through precision fermentation. They replicate the exact functional and nutritional profiles of bovine caseins and whey, potentially overcoming the sensory and textural deficiencies inherent in traditional plant-based analogs [54].

Various additives are employed as stabilizers, gelling agents, and preservatives for the optimization of the physicochemical, rheological, and sensorial properties of yogurt. Robust structural integrity is provided by synthetic stabilizers such as polyethylene oxide polymers and acrylate copolymers; however, their use is increasingly scrutinized due to environmental concerns, potential toxicity, and inferior biocompatibility compared to natural alternatives. Common food-grade stabilizers include pectin, gelatin, starch, guar gum, xanthan gum, CMC and carrageenan. These hydrocolloids are used in the food industry as thickeners [59]. Other modified additives have also been reported by Bankole et al. [44]. Levan, a fructan, has also been reported by Li et al. [60], showing prebiotic potential. Modified stabilizers, such as carrageenan, have been tentatively linked to inflammatory and digestive complications [44]. However, its direct interaction with milk proteins to create smooth, creamy textures and prevent whey separation has made carrageenan very popular. Its multifaceted role has been described by Kalsi et al. [61]. Natural additives have been investigated to enhance both the technological and functional profiles of yogurt. Chickpea flour has been shown to improve the antioxidant and thickening properties of stirred bio-yogurt while acting as a prebiotic that boosts *Bifidobacterium* and *Lactobacillus* counts [62]. Plant-based yogurts benefit from the addition of quinoa and soy; their combination leads to the enhancement of texturizing, rheological, and fermentation properties, while increases in antioxidant activity and digestibility arise from the fermentation process [63].

Beyond ingredient optimization, novel processing methodologies and Industry 4.0 (IR 4.0) technologies facilitate contemporary yogurt manufacturing (Figure 2). The smart manufacturing principles of Industry 4.0 aim to create a hyper-connected industrial environment that enhances competitiveness and food safety [64]. Fermentation kinetics have been monitored using advanced techniques, such as the integration of ultrasonic sensors with machine learning models. These sensors provide continuous, real-time monitoring of critical fermentation variables, including pH, temperature, dissolved oxygen, biomass, substrate consumption, gas composition, and metabolite concentrations. This enables the early detection of process deviations and potential microbial contamination. IoT architectures interconnect the sensing devices within the production systems, facilitating traceability, remote monitoring, and rapid communication between equipment and control platforms [65]. Machine learning algorithms transform high-volume sensor outputs into predictive models capable of identifying contamination risks, forecasting microbial growth kinetics, detecting abnormal fermentation parameters, and optimizing process parameters to increase yield and consistency. Digital twins are virtual replicas of biological systems and processes that simulate fermentation dynamics and enable scenario testing, predictive process tuning, and optimization without interrupting production. Big Data systems aggregate real-time information from multiple batches, environmental sources, and process stages to reveal patterns that might otherwise go unnoticed with conventional analysis [66]. Together, these technologies enable predictive risk identification for faster intervention, improve metabolite formation, and optimize overall product quality. However, despite their great theoretical potential, the practical implementation of these technologies requires high infrastructure costs and highly trained personnel, in addition to the difficulty of integrating digital systems into existing production environments, which hinders their widespread adoption.

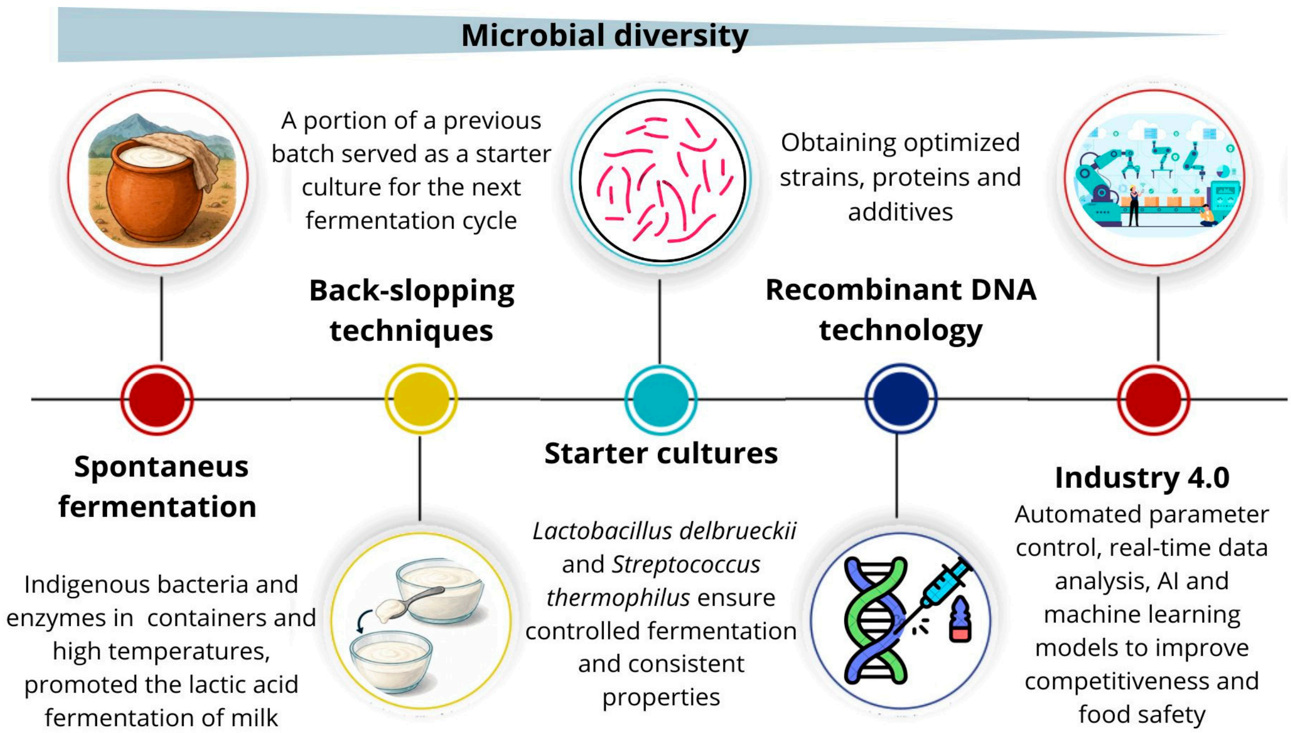

Figure 2. Yogurt production throughout history: from ancestral spontaneous fermentation to Industry 4.0.

Plant-based tiger nut (*Cyperus esculentus*) yogurts fortified with fresh *Moringa oleifera* leaf tea as functional foods have been reported by Yeboah et al. (2026) [67]. They significantly enhanced their nutritional and microbial properties, considering them to be suitable dairy substitutes. *Moringa oleifera*, commonly referred to as the "miracle tree," is a "superfood" due to its rich content of antioxidants, anti-inflammatory agents, and nutrients that promote cellular health and disease prevention [68,69]. Tiger nut (*Cyperus esculentus*) is a promising functional food ingredient due to its rich nutritional profile, including high levels of dietary fibers, mono- and disaccharides and oleic acid, as well as moderate amounts of proteins, essential minerals, and vitamins C and E [70].

4.2. About Cheese

From a technological perspective, the microbiota of cheese can be categorized into three groups: (i) primary starter cultures, mainly LAB, responsible for initiating fermentation and the subsequent acidification of milk and curd; (ii) specific bacteria, yeasts, and molds added at various production stages (such as surface application or internal inoculation in blue cheeses) to enhance ripening and sensory profiles, named secondary adjunct cultures; and (iii) microorganisms that enter the process spontaneously, named adventitious microbiota (Table 1). However, these microorganisms can also occasionally lead to quality defects or undesirable off-flavors as well as helping to develop the unique texture and flavor of different varieties [70,71].

A more intense flavor and aroma is exhibited by raw milk cheeses compared to those made from pasteurized milk, as the milk's indigenous microbiota impart unique sensory properties. However, modern industrial production typically relies on starter cultures for hygiene and quality consistency and restoration of the traditional flavor profile in regions where raw milk use is restricted—as well as cases where alterations in the original microbiota are performed to improve microbiological quality. Furthermore, reinforcement of the authentic characteristics of Protected Designation of Origin (PDO) cheeses, achieving a sensory quality that more closely resembles traditional products, can be carried out by employing selected microbial cultures. Ruvalcaba et al. [72] produced Adobera cheese—an authentic, pasta filata-type cheese from Western Mexico—and used standardized methods with pasteurized milk and indigenous starter cultures (*Lactobacillus* and *Leuconostoc* strains). Their results showed that pasteurization promoted water retention in the cheese matrix, impacting both texture and color profiles. Hence, raw-milk cheeses were harder, more cohesive, and less elastic than their pasteurized counterparts, whereas ripening markers remained significantly higher in the raw-milk versions throughout all sampling stages.

Over the last four decades, numerous research has been published on the isolation and characterization of thousands of LAB and other microorganisms from raw milk, focusing on their application in traditional cheesemaking. Raw milk microbiota include genera such as *Lactococcus*, *Leuconostoc*, *Enterococcus*, *Streptococcus*, *Micrococcus*, and *Staphylococcus*, playing a vital role in the ripening and flavor development of these cheeses [73]. López et al. [74] worked on valdeón cheese, a traditional Spanish blue cheese, and identified nearly 500 strains, with 95% of aerobic mesophiles being LAB. They reported dominant genera such as *Enterococcus* (40.4%) and *Lactococcus* (42.2%), *Lactobacillus* (4.1%) and *Leuconostoc* (5.0%). The most prevalent species was *Lactococcus lactis* subsp. *lactis* (31.1%), alongside various *Enterococcus* species, such as *Enterococcus faecalis* (24.7%).

The last decade has seen a significant shift toward indigenous yeasts. These microorganisms play a key role in the ripening of soft, semi-hard, and mold-rind cheeses, as well as fresh varieties due to their preferential growth under aerobic conditions. *Debaryomyces hansenii*, *Kluyveromyces lactis*, and *Yarrowia lipolytica* yeasts act as auxiliary cultures to enhance the production of various PDO cheeses [75].

A wide array of aged, ripened, and blue cheeses with many well-known varieties, such as Cheddar, Gouda, Parmesan, and Camembert, originated during the middle Ages. In recent decades, cheese consumption has surged, particularly as a key ingredient in foods like pizza, burgers, and breads [76]. Distinct physical properties, ranging from firmness and creaminess to varying degrees of liquidity have been achieved along variations in the processing and ripening periods of different cheeses.

A patented method for producing processed cheese that used emulsification to extend its shelf life was described in 1916 by James Kraft. Consumers prioritize texture over nutritional value [32] as far as this and other processed cheeses are concerned.

New technologies were implemented to control and accelerate ripening, such as the addition of animal or microbial enzymes and the use of attenuated or genetically modified starter cultures [77], between the 1980s and 2000s.

By the late 2000s, culture-independent "omics" technologies have been developed to detect cheese microbial ecosystems. These methods explore the entire microbial genome without the need for prior culturing by analyzing microbial DNA or RNA directly. Researchers can evaluate how specific strains influence cheese flavor through a combination of strain-level metagenomics with metabolomics (targeting volatile compounds). Flavor development can be studied by the association between the volatilome and metagenomic species clusters [78]. The correlation of dynamic microbial ecology—including diversity, succession, and community interactions—with metabolism during cheesemaking and ripening [75] can be achieved using a multi-omics approach. High-throughput DNA sequencing (HTS) has been applied recently to allow for a detailed analysis of the composition and functional potential of the microbiota in traditional raw milk cheeses. The cheese core is typically dominated by LAB belonging to the genera *Lactococcus*, *Lactobacillus*, *Enterococcus*, *Streptococcus*, and *Leuconostoc* [73].

Plant-based milk substitutes consist of plant proteins following homogenization with emulsifiers, stabilizers, and flavorings to create colloidal suspensions that mimic the appearance and consistency of cow's milk [32]. This increases consumer demand.

The larger molecular size and complex quaternary structures of plant-based proteins means they differ significantly from casein [54]. Attempts to mimic dairy-like properties have been made by blending cow and soy milk—creating 'partial dairy cheese analogues'. However, these efforts often resulted in inferior textures, characterized by excessive adhesiveness, reduced firmness, and off-flavors [79].

Fermentation is still a powerful tool for enhancement of the sensory profile, nutritional value, and shelf life of plant-based products [1]. Sufu, an ancient Chinese cheese-like product, is an example, made by the coagulation of soy milk followed by fungal or bacterial fermentation [80]. For successful production, starter cultures must effectively dominate microflora such as LAB [1]. For instance, Li et al. [81] showed the effect of an optimized soy cheese processed through the combination of glucono delta-lactone, LAB fermentation, and enzymatic hydrolysis, achieving superior spreadability and a stable, homogeneous structure.

Recent research demonstrated the addition of specific *Bacillus* strains, such as *B. velezensis*, *B. amyloliquefaciens*, and *B. subtilis* alongside *L. lactis*, *L. cremoris*, and *Leuconostoc mesenteroides*. They significantly improved the quality of plant-based cheese. These *Bacillus* strains enhanced proteolysis and extended shelf life by inhibiting mold growth. *Bacillus velezensis* FUA2155 increased glutamate levels, hence refining the flavor profile and overall preservation of these analogs [82].

Yogurt and cheese exemplify the impact of ancestral fermentation practices on contemporary food systems, highlighting the link between traditional knowledge, microbiology, nutrition, and modern food technology. In this respect, they present a fundamental challenge for modern biotechnology: balancing traditional sensory characteristics with industrial standardization and food safety. Integrating omics technologies and precision fermentation approaches can improve strain selection and process optimization while preserving the cultural identity of these ancestral dairy products.

5. Traditional and Emerging Fermented Foods: Associated Microorganisms, Bioactive Metabolites, and Functional Properties

5.1. Cocoa Bean Fermentation

Cocoa bean fermentation is crucial for chocolate production. The fermentation typically begins with the consumption of sugars by yeasts and LAB, followed by the oxidation of ethanol and lactic acid by acetic acid bacteria (AAB) [83,84]. Key metabolites like ethanol, lactic acid, and acetic acid are produced, contributing to flavor development [85]. Critical processes in cocoa production are fermentation and drying, since they significantly influence its sensory and chemical properties.

Production of the desirable volatile compounds while minimizing the development of off-flavors can be achieved by an optimal fermentation duration of approximately six days, followed by drying at 70 °C [86]. The fermentation dynamics and final product quality are affected by the genetic composition of cocoa cultivars [87].

Carbohydrate metabolism and the production of organic acids contribute to the fermentation process through key genera and families including *Saccharomyces* (Y), *Lactobacillaceae* (LAB), and *Acetobacter* (AAB) [88].

López-Pentes et al. [89] employed Illumina-based shotgun metagenomic sequencing for the characterization of microbial community dynamics and metabolic potential across two post-harvest cocoa processing routes (R1 and R2) in Boyacá, Colombia, encompassing both fermentation and drying stages.

A shift from a yeast-dominated profile, mainly *Saccharomyces* and *Pichia*, during fermentation, to the emergence of the filamentous fungus *Aspergillus* during drying was detected for fungal communities. On the other hand, a transition between diverse *Enterobacteriaceae* in early fermentation to a near-complete dominance of *Acetobacter*, which persisted throughout drying, was detected for bacterial populations.

5.2. Fermented Stevia

Stevia rebaudiana is a natural, zero-calorie sweetener due to its high content of steviol glycosides (stevioside and rebaudioside A), which deliver intense sweetness with negligible caloric contribution [90–92]. Stevia leaves can also be used as a new substrate and nitrogen source in kombucha production, yielding a functional beverage with high drinkability and potential health benefits [93].

Fermentation changes the phytochemical composition of stevia to a great extent. Fermentation is facilitated by yeasts and LAB, which change steviol glycosides, producing new bioactive metabolites (such as terpenoids), and increase the amount of healthy chemicals [94]. An improvement in sensory attributes and the extensive biotransformation of steviol glycosides, releasing bound phenolic compounds and generating novel metabolites with enhanced biological activities, are facilitated by fermentation [95,96].

Moreover, stevia extract was shown to lead to improved antioxidant, antibacterial, antidiabetic, and anticancer activities in vitro and in animal models. Its potent gut microbiota modulation ability, and effective alleviation of dysbiosis, causing a reduction in associated inflammatory markers, are its major characteristics. Of course these effects are linked to the specific experimental model and should not be generalized as established human health benefits.

Stevia rebaudiana can be fermented with specific LAB strains, such as *Lactiplantibacillus plantarum* and *Lacticaseibacillus pentosus* isolated from bee bread. These strains efficiently utilize stevia leaf powder and steviosides. Acid and bile tolerance and adhesion to intestinal cells are some of the desirable probiotic qualities exhibited by these strains, which also show significant antidiabetic, antioxidant, and antifungal activities [95].

Specific strains of *Streptomyces*, such as *Streptomyces antibioticus* M7 isolated from the stevia rhizosphere, produce actinomycin with potent antibacterial properties [97]. *Lactobacillus plantarum* targeting steviol glycosides has been reported by Kim et al. [98] and *Pediococcus pentosaceus* was reported to target stevia extract by Ma et al. [99].

5.3. Fermented Juices

LAB-fermented fruit juices could exert antidiabetic effects. However, generalized comments regarding established human health benefits should be avoided as these could be linked to the specific experimental model employed. For instance, fermentation with *Lactobacillus plantarum* FNCC 0027 could improve the functional activity of Jamaican cherry juice and enhance the inhibition of diabetes-related enzymes, as reported by Frediansyah et al. [100].

Similarly fermented pumpkin juice using *L. plantarum*, as reported by Barrón et al. (2022) [101], showed antioxidant, α-glucosidase inhibition, and hypoglycemic properties.

Xu et al. (2026) [102] reported that fermentation of Goji berry (*Lycium barbarum* L.), rich in bioactive compounds (polysaccharides, polyphenols, carotenoids and amino acids), could further enhance its functional efficacy. The impact of *Lactobacillus paracasei* fermentation on the quality attributes of goji berry juice and its in vivo antihyperglycemic efficacy was tested here. Total flavonoids (+31.8%) and polysaccharides (+5.4%) showed enhanced antioxidant activity, and volatile aroma enrichment relative to unfermented juice was significantly increased by fermentation [102]. This study was carried out using an experimental model with mice. Hence, it is also essential to state that both quality attributes and antidiabetic efficacy in relation to the integrative effects of *L. paracasei*-fermented goji berry juice remain insufficiently elucidated, particularly with regard to compositional enhancement, oxidative stress regulation, and gut microbiota-derived short-chain fatty acids (SCFAs).

5.4. Microalgal Fermentation

Algal fermentation is a process employed for the enhancement of nutritional and functional properties of algae, while improving their digestibility, bioaccessibility and sensory properties [103]. Specifically, lactic acid fermentation has been widely applied in food systems generating or releasing bacteriocins, peptides, and physically entrapped substances [104]. The health-promoting potential of microalgal biomass may be enhanced through fermentation, making it attractive for use in functional foods and nutraceuticals [105].

Chlorella vulgaris is particularly attractive due to its high protein (≈43–58% DW) and carbohydrate (≈12–55% DW) contents, as well as its role as a source of functional lipids, water-soluble vitamins and pigments [106]. *C. vulgaris* is a promising substrate for microbial fermentation, particularly by LAB, due to its rigid cell wall full of polysaccharides. However, a barrier that limits the accessibility of intracellular nutrients is being formed by resistant polysaccharides and glycoproteins, thereby hindering fermentation efficiency [107].

Bilgin et al. [108] studied the combined effect of enzymatic pretreatment (ultrasound-assisted hydrolysis, hydrothermal treatment, and enzymatic hydrolysis) and microbial fermentation on the enhancement of the biofunctional value of *C. vulgaris* and proved it to be a sustainable strategy for developing natural antioxidants and antimicrobial agents for food, nutraceutical, and cosmetic applications. Table 1 presents traditional and emerging fermented foods along with their associated microorganisms, key metabolites and advantages.

Table 1. Traditional and emerging fermented foods: associated microorganisms, bioactive metabolites, and functional properties.

Fermented Food	Main Microorganisms Involved	Key Metabolites Produced	Key Advantages	References
Yogurt	*Streptococcus thermophilus* and *Lactobacillus delbrueckii* subsp. *Bulgaricus*.	Organic acids, bioactive peptides, fatty acids, bacteriocins	Inhibits spoilage and pathogenic bacteria. Enhances texture, flavor, and aroma. Improves vitamin, mineral, and amino acid bioavailability.	[36–38]
Cheese	(i) Starter cultures, mainly LAB (*Enterococcus*, *Lactococcus*, former genus *Lactobacillus*, *Leuconostoc*); (ii) secondary adjunct cultures: specific bacteria, yeasts (*Debaryomyces hansenii*, *Kluyveromyces lactis*, and *Yarrowia lipolytica*, and molds); (iii) adventitious microbiota.	Organics acids, free fatty acids, ketones, alcohols, esters, aldehydes	(i) Initiates rapid fermentation and curd acidification; (ii) promotes flavor development and unique textures; (iii) optimizes ripening and sensory profiles.	[71–76]
Plant-based cheeses	*Bacillus* strains, Lactococcus, *Bacillus*, *Leuconostoc*	Bioactive peptides glutamate levels	Improved the quality and flavor profile and extended shelf life.	[80–82]

Table 1. *Cont.*

Fermented Food	Main Microorganisms Involved	Key Metabolites Produced	Key Advantages	References
Chocolate	Yeasts (*Saccharomyces* and *Pichia*), LAB, (*Limosilactobacillus fermentum*, *Lactiplantibacillus plantarum*, *Lactobacillus cacaonum*, *Fructobacillus pseudoficulneus*, *Leuconostoc* and *Streptococcus* spp.); acetic acid bacteria (*Acetobacter*).	Ethanol, lactic acid, and acetic acid	Influenced sensory and chemical properties, and flavor development.	[87–89]
Fermented stevia	*Lactiplantibacillus plantarum* and *Lacticaseibacillus pentosus*, *Pediococcus pentosaceus*, and *Streptomyces*.	Steviol glycosides, phenolic compounds, bioactive metabolites (terpenoids)	Improvement in health and sensory attributes. Modulation of gut microbiota.	[90–92]
Fermented juices	LAB strains.	Total flavonoids and polysaccharides, volatile aroma, polyphenols, carotenoids and amino acids	Improved the functional, antioxidant activity, enhanced the inhibition of diabetes-related enzymes.	[100–102]
Fermented microalgal	LAB strains.	Bacteriocins, peptides, amino acids and lactic acid	Upgrades nutritional and functional values. Improves digestibility and bioaccessibility. Elevates overall sensory properties.	[103–108]

6. Functional Attributes of Fermented Foods: From Microbial Metabolism to Mechanistic Evidence

Fermentation is presented as a transformative process that enhances the functional properties of foods [1,2] but also as a biological preservation method, driven by the production of organic acids, ethanol, and bacteriocins that inhibit spoilage microorganisms and pathogens. Fermented foods play a key role in traditional diets and are often accompanied by empirical claims of health-promoting effects. Fermentation modifies the food matrix, hence improving digestibility, the bioavailability of nutrients, and the presence of bioactive compounds, and thereby offering benefits that extend beyond basic nutrition [4].

Current epidemiological data indicate that high consumption of fermented foods may lower the risk of chronic diseases while promoting overall health and life expectancy [10,109,110]. However, the panel of experts convened by the International Scientific Association for Probiotics and Prebiotics (ISAPP), which developed the definition of fermented foods in 2019, warns that there is a lack of high-quality, randomized controlled trials (RCTs) verifying the health impacts of many fermented items [4].

The benefits of consuming yogurt and fermented milk, related to improved cardiovascular health, a lower risk of type 2 diabetes, and reductions in obesity markers such as BMI and waist circumference, have been well-documented in several randomized clinical trials [110]. Also, at least one RCT has explored the physiological effects of other fermented staples, such as kefir, kimchi, sauerkraut, natto, vinegar, and sourdough bread [4].

Current scientific evidence suggests that the health-promoting effects of fermented foods occur through several distinct pathways: i—the enzymatic transformation of raw substrates; ii—the biosynthesis of bioactive metabolites; iii—the favorable modulation of the gut microbiota [1,4].

6.1. Enzymatic Transformation of Raw Substrates

6.1.1. Increased Digestibility of Complex Macromolecules and Elimination of Antinutritional Factors

The microbial metabolism of complex macromolecules increases their digestibility and nutritional value, as well as modifying the functional and sensory profile of foods. Since microorganisms cannot directly absorb large polysaccharides, extracellular enzymes are required to break them down into smaller units. Starch degradation depends on amylases from bacteria, molds, and actinomycetes. Cellulose degradation is driven by cellulases from specific microbes, such as *Trichoderma* (*T.*) *viride*, *T. reesei*, bacteria, and actinomycetes [111]. Pectin hydrolysis utilizes pectinases from bacteria, molds (e.g., *Aspergillus* (*A.*) *goneii*, *A. niger*), and yeasts, generating bioactive acids and alcohols [112]. Microbial proteases convert complex proteins into absorbable peptides and amino acids. *Bacillus* primarily produce alkaline proteases, while the molds *A. niger* and *A. oryzae* primarily produce acid proteases [113]. LAB develop in dairy products and degrade casein and other milk proteins, increasing their digestibility and reducing their allergenic potential [114]. The subsequent transamination, deamination, and decarboxylation of amino acids produce bioactive aldehydes, acids, and alcohols. Finally, lipases from bacteria (*Bacillus*, *Pseudomonas*, *Staphylococcus*), molds (*Rhizopus oryzae*, *A. niger*), and yeasts (*Candida*) hydrolyze lipids into glycerol and fatty acids [115]. Their subsequent metabolism generates bioactive products that also enhance the sensory properties of food.

On the other hand, yogurt is generally classified as a low-glycemic-index (GI) food. This means that it is digested slowly and causes a gradual rise in blood sugar, rather than sudden spikes. The GI value for plain yogurt was 27 ± 11, compared with 41 ± 11 for sweetened yogurt ($p < 0.0001$). This difference is not explained by the sugar itself, but by the higher protein-to-carbohydrate ratio in plain yogurt [8]. Furthermore, numerous studies, as reviewed in Savaiano et al. [116], showed that yogurt consumption improves lactose digestion compared to other dairy products in lactose-intolerant individuals. This occurs because bacterial lactases survive the stomach acid, because yogurt acts as a buffer. In the small intestine, a higher pH and slower intestinal transit activate the enzymes that digest lactose sufficiently to prevent digestive symptoms [13,110].

Moreover, fermentable oligosaccharides, disaccharides, monosaccharides, and polyols (FODMAPs) can be reduced through sourdough fermentation and extended fermentation times, hence leading to a reduction in gastrointestinal symptoms such as flatulence, pain, and stomach-rumbling in IBS patients compared to regular breads [117]. Notably, it should be considered that, as a restrictive diet, the low-FODMAP diet carries risks of nutritional deficiencies and promoting eating disorders, in addition to inducing potentially undesirable changes in the gut microbiota [118]. Therefore, besides clinical judgment, fermented foods and the administration of prebiotics may be an effective strategy for managing dietary restrictions in patients with functional gut symptoms [119].

LAB fermentation can modify food preservation as well as sensory and functional properties, and reduce toxicity, as well as increasing the content of active ingredients in herbal medicines [120,121]. The structure and function of plant polysaccharides can be altered and potentially enhanced by LAB fermentation [122,123].

The fermentation of blue honeysuckle polysaccharides by *Lacticaseibacillus rhamnosus* 6224 and other strains altered their structural characteristics and bioactivity [124]. *Lactiplantibacillus plantarum* NCU 116 fermentation of Momordica charantia polysaccharides has been reported to reduce their average molecular weight and improve their antidiabetic function [125]. *Limosilactobacillus reuteri* DSM17938 has been proven to be a safe probiotic strain and effective in the prevention and treatment of various diseases both in experimental models and in human trials [126,127]. Di Porzio at al. [128] suggested its potential as a preventive strategy against the development of diet-related diseases, type 2 diabetes and metabolic syndrome and the prevention of liver disorder in an adult rat model.

Liu et al. [129] reported that LAB fermentation can biotransform plant polysaccharides and may enhance their bioactivity. They investigated fermentation with *Limosilactobacillus reuteri* DSM17938 and found that fermentation affects the structure of *Gastrodia elata* polysaccharides and their potential benefits in type 2 diabetes mellitus (T2DM) in a murine model.

Furthermore, fermentation eliminates anti-nutritional factors (ANFs) such as oxalates and tannins, and hence is critical for biodetoxification. Nagarajan et al. [120] investigated the fermentation of a linseed beverage using *Lactobacillus acidophilus*, *Bacillus mesentericus*, *Saccharomyces boulardii*, *Saccharomyces ellipsoideus*, and the new isolate LAB-3, and showed significant reductions in total phenolics and tannins, particularly in treatments involving *L. acidophilus* and isolate LAB-3. The highest reduction in cyanogenic glycosides was achieved with *L. acidophilus* (66%), followed by isolate LAB-3 (65%) and *B. mesentericus* (58%). Although some authors suggest possible beneficial effects of these ingredients in human health, these still need to be studied in greater detail. On the other hand, soybean meal is the main source of protein in animal feed, but its antinutritional components affect animal growth and immunity. Therefore, some recent studies have evaluated strategies including yeast fermentation, physical and chemical methods, and protease hydrolysis to reduce antinutritional factors and accumulate beneficial metabolites [130].

6.1.2. Enhancement of Concentration and Bioaccessibility of Antioxidant Compounds

The ability of LAB to metabolize phenolic compounds present in different substrates and increase their bioavailability as well as antioxidant activity has been widely reported [1]. Certain strains cause the biotransformation of phenolic compounds through deesterification or hydrolysis, which improves the functional profile of the food and provides defensive enzymes (catalases, peroxidases) with the potential to prevent oxidative stress and chronic diseases [131,132]. Recently, researchers investigated the transformation of bioactive compounds from avocado leaves through lactic acid fermentation to enhance their functional properties. Fermentation increased the total content of phenolic compounds, particularly with strains of *Pediococcus pentosaceus* (71%), followed by *Levilactobacillus brevis* (62%) and *Pediococcus acidilactici* (55%), while the strains *Lactiplantibacillus plantarum* CECT 748T and *Pediococcus pentosaceus* CECT 4695T stood out as inducing the highest antioxidant capacity in the extracts [131].

The enzymatic transformation of food substrates is a fundamental mechanism through which fermentation can promote health. Microbial enzymes degrade complex macromolecules and eliminate antinutritional factors, optimizing nutrient digestibility and bioavailability while generating bioactive metabolites with therapeutic potential. However, due to the internal variability of substrates and the diverse processing conditions, generalizations regarding these effects should be avoided. Furthermore, most current research is limited to in vitro characterization at the laboratory scale, highlighting a lack of industrial-scale studies. Therefore, to overcome these limitations and consolidate translational application, a rigorous standardization of processes is essential, along with the development of randomized clinical trials in experimental models and humans.

6.2. Biosynthesis of Bioactive Metabolites

6.2.1. Vitamins

Essential vitamins (such as B-complex and K) are biosynthesized by specific LAB strains both during food fermentation and in situ in the gastrointestinal (GI) tract. B-group vitamins play important roles in metabolic processes, such as energy production and red blood cell synthesis [133], while vitamin K is important for blood clotting and bone health [134]. Most studies have focused on the search for vitamin-producing strains in vitro. Riboflavin production has been described in a variety of lab species, with the following standing out: *L. rhamnosus*, *L. plantarum*, *L. fermentum*, *L. mucosae*, *Leuconostoc mesenteroides*, *Enterococcus* (*E.*) *faecium*, *L. lactis* subsp. *lactis*, and *L. acidophilus*. Cobalamin biosynthesis has been reported in *L. reuteri*, *L. plantarum*, *L. coryniformis*, *L. fermentum*, *L. rhamnosus*, *L. casei*, *E. faecium*, *E. faecalis*, *Furfurilactobacillus rossiae*, among others [1,133].

Although there is a lack of in vivo assays, the administration of folate-producing bifidobacteria was shown to cause an increased fecal level of folate in both rats and humans [135]. Furthermore, administering soy milk fermented with a strain of *Limosilactobacillus reuteri* CRL 1098 prevented the development of all symptoms observed as a consequence of nutritional vitamin B12 deficiency, both in female mice and their offspring [136].

6.2.2. Exopolysaccharides

Additionally, exopolysaccharides that can act as antioxidants, serve as barriers against pathogens, and exhibit hypocholesterolemic activities, among other benefits, can be secreted by certain strains [7,137,138]. Crude polysaccharides from *Lactobacillus helveticus* MB2-1 showed high antioxidant and metal ion-chelating activities in vitro [137]. OLL1073R-1 was identified as the most robust producer of EPS in an analysis of 139 strains of *L. delbrueckii* subsp. *bulgaricus*. Following oral administration of this EPS or yogurt fermented with OLL1073R-1, natural killer (NK) cell activity increased and IFN-γ production via an IL-12- and IL-18-mediated mechanism was induced. Hence, traditional Bulgarian yogurt may exert immunostimulatory effects when prepared with selected starter strains [7].

6.2.3. Gamma-Aminobutyric Acid

Gamma-aminobutyric acid (GABA) is a non-protein amino acid produced during fermentation showing neurotransmitter functions. Neuroprotective effects of GABA have been reported, as well as improved sleep quality, relief from depression and pain, while its potential antidiabetic, antihypertensive and anti-inflammatory properties are under study [11]. Pokusaeva et al. [139] reported that oral administration of a GABA-producing *Bifidobacterium* strain increased GABA levels in the cecum and reduced the excitability of specific sensory neurons in the colon, which are the general causes of abdominal pain. While numerous studies (reviewed in Braga et al. [140]) indicate the potential role of GABA as a modulator in the gut–brain axis, most published studies have focused on GABA-producing strains and the involvement of the gut microbiota and GABA in mental health and brain diseases, and there is a lack of randomized in vivo studies. In this sense, LAB are the most-studied GABA-producing strains; however, their production has also been reported by strains of fungi and yeasts such as LAB strains, *Rhodotorula*, *Neurospora crassa*, *Aspergillus nidulans* and *Aspergillus niger*, *Monascus* spp., *Saccharomyces*, and *Candida* spp., among others [141]. *L. brevis* CRL 2013 can produce up to 2.7 g/L of GABA [11], while under optimized fermentation conditions in a bioreactor, *L. brevis* NCL912 achieved 100 g/L of GABA [142].

6.2.4. Short-Chain Fatty Acids

Short-chain fatty acids (SCFAs), primarily acetate, propionate, and butyrate, are key microbial metabolites produced through the fermentation of dietary fibers by the gut microbiota. These molecules serve as an energy source for colonocytes (particularly butyrate), regulating intestinal barrier integrity, and modulating immune response, and hence playing a central role in host–microbe interactions. SCFAs activate G protein-coupled receptors (e.g., GPR41, GPR43, and GPR109A) and inhibit histone deacetylases, thereby influencing gene expression and inflammatory pathways. They impact glucose homeostasis, lipid metabolism, and appetite control, contributing to systemic metabolic regulation [143,144]. Pingitore et al. [145] reported that SCFAs, such as acetate and propionate, enhanced glucose-stimulated insulin secretion and reduced apoptosis in mouse and human islets by activating the FFAR2 receptor. Therefore, the role of SCFAs in regulating pancreatic function through Gq-coupled signaling pathways is highlighted. Alterations in SCFA production have been associated with inflammatory bowel disease, obesity, and metabolic syndrome, highlighting their importance as both biomarkers and potential therapeutic targets in microbiome-related disorders [146,147].

In addition to production by gut microorganisms, fermentation is a useful tool for increasing SCFA content. While few studies have directly investigated the increase in SCFAs in fermented foods, the results confirm that SCFA levels are higher compared to non-fermented products [148]. Asarat et al. [149] showed that SCFA production in skim milk was dependent on the strain and the prebiotic added as a substrate. The highest SCFA production (acetate 2.72 mM, propionate 0.92 mM, and butyrate 0.41 mM) was observed with *Bifidobacterium animalis* subsp. *lactis* when inulin was added as a prebiotic. Considering the differences in the metabolic pathways of the microbial strains, an inter-genus combination can optimize SCFA production, as demonstrated by Binosha et al. [150]. Indeed, the authors reported a higher SCFA concentration during rice fiber fermentation with different bacterial strains, including *Lactobacillus* and *Bifidobacterium*. Along these lines, the fermentation of kombucha with the addition of pollen using a symbiotic culture of bacteria and yeast (SCOBY), including LAB, acetobacteria, and yeast, resulted in a significant increase in SCFAs [151]. Finally, due to their fiber content, fruit and vegetable juices are good substrates for SCFA production, as reported in carrot juice fermented with *L. rhamnosus* GG.

These two processes, i.e., SCFAs produced by gut microbiota and SCFAs formed in fermented foods, differ in production site, dose, absorption, and physiological relevance.

The synthesis of bioactive metabolites during fermentation enhances their functionality, providing benefits beyond basic nutrition. Organic acids, vitamins, exopolysaccharides, short-chain fatty acids (SCFAs), and other bioactive compounds generated during fermentation can contribute to antimicrobial activity, immune modulation, metabolic regulation, and other functions. However, translational challenges related to the bioavailability and clinical relevance of these metabolites persist, underscoring the importance of integrating in vitro assays with animal and human studies to better define their potential for health promotion.

6.3. Modulation of the Gut Microbiota

The gut microbiota consists of a diverse collection of microorganisms—including bacteria, viruses, fungi, and archaea—that inhabit the digestive tract from the esophagus to the intestines [30]. The role of gut microbiota research in human health has been highlighted in the last few years, specifically regarding its relationship with diet, environment, and socio-cultural factors [152]. Indeed, the diversity of microorganisms that co-evolved with humans from their earliest days as a species has been gradually modified and depleted due to the social, demographic, technological, and nutritional changes in the post-industrial era. The consequence is a higher incidence of a group of diseases related to a hyperreactive immune system [153]. One strategy for restoring the gut microbiota is the consumption of foods fermented with live microbes.

The consumption of fermented foods can increase dietary microbe intake by up to 10,000-fold, suggesting a regular introduction of transient yet functional microbes into the indigenous intestinal ecosystem through the daily intake of 'living' fermented foods [154]. Many traditional fermented products, such as yogurt, kefir, kimchi, and kombucha, typically contain high concentrations of viable cells, often ranging from 10^6 to 10^9 per gram or milliliter [4,13]. The harsh conditions of the gastrointestinal tract, such as an acidic pH and environmental stressors, can be overcome by these robust microbial consortia, allowing for their integration into the resident microbiota with effects on the host's physiological functions [14]. However, many food-derived microbes are transient and do not necessarily colonize the gut. Hence, survival, persistence, and effects are strain-, matrix-, dose-, and host-dependent.

Taylor et al. [155] analyzed stool samples from 6811 individuals in the American Gut Project—including 115 frequent consumers of fermented foods—to correlate consumption with distinct gut microbiota and fecal metabolome profiles. The presence of health-promoting metabolites, such as conjugated linoleic acid, was reported.

The effects of daily kefir consumption on gut microbiota and athletic performance in 21 professional female soccer players was also assessed. Kefir intake increased microbial diversity and the abundance of beneficial bacteria such as *Akkermansia muciniphila* and *Faecalibacterium prausnitzii* following 28 days. Associations between microbiota, diet, and body composition were also observed. Modulation of gut microbiota and support of athletic performance could be achieved by kefir, although longer-term studies are needed [10].

6.4. Fermented Foods and Metabolic Health

The association between fermented foods and metabolic health also needs to be elucidated, and more specifically their relationship with metabolic syndrome (MetS), Type 2 diabetes mellitus (T2DM), and related non-communicable diseases (NCDs). A nonlinear inverse association between total dairy intake and prediabetes risk has been reported in a recent 2024 meta-analysis of prospective cohort studies. Prediabetes risk may be lowered by consumption of moderate dairy-fermented food [156]. A prospective cohort study of 3616 healthy adults reported a significant reduction in the risk of developing MetS over 2 y through yogurt consumption [157]. A better overall diet quality in both adults and children [158,159], along with reduced visceral fat and healthier dietary scores [160], has been associated with yogurt intake. Mirjalili et al. [161] reported on the effect of probiotic yogurt to improve glycemic control and lipid profile in patients with T2DM showing, for the probiotic group, decreased HbA1c, decreased TC, decreased LDL-c, and no significant change in TG or HDL-c. A general improvement in glycemic control, reduction in fasting blood glucose, and effects on additional aspects of metabolic health may arise from the impact of fermented foods, as reported from both observational and interventional studies, highlighting the impact of fermented foods on reducing the risk of T2DM and improving metabolic parameters relevant to MetS and cardiovascular disease (CVD) [162].

7. Fermented Foods as Vehicles of Biotics

Fermented foods are increasingly recognized as important carriers of biologically active compounds referred to as “biotics”. They can modulate host physiology and contribute to health. These include probiotics (live microorganisms that confer health benefits when administered in adequate amounts), prebiotics (substrates that are selectively used by the host microorganisms, conferring a health benefit), and postbiotics (preparation of inanimate microorganisms and/or their components that confer a health benefit on the host) [14].

7.1. Probiotic Fermented Food

Probiotics are among the most studied biotic components in fermented foods. Genera such as *Lactobacillus*, *Leuconostoc*, *Streptococcus*, and *Bifidobacterium* are frequently associated with dairy foods, vegetables, and cereals. These microorganisms may contribute to gut microbial balance, enhance barrier function, and modulate immune responses when present in sufficient concentrations and able to survive gastrointestinal transit [14]. However, it should be stressed that not all fermented foods meet the criteria required for probiotic designation, since there is a differentiation between foods that contain live microbes and those that deliver clinically validated probiotic strains [163]. Although it has been implied in other studies that fermented foods generally function as probiotic foods, there is a differentiation between live microbes, probiotics, prebiotics, postbiotics, and microbial metabolites. As Ji et al. [164] reported, along with other researchers, probiotics are live microorganisms providing health benefits when administered in adequate amounts [165]; prebiotics are nondigestible substances such as dietary fibers promoting the growth and activity of beneficial gut bacteria [166]; and postbiotics are produced by probiotics during their growth, hence contributing to gut health [167,168]. Prebiotics, probiotics, and postbiotics modulate the gut microbiome composition, hence enhancing the production of anti-inflammatory metabolites and thus maintaining and restoring gastrointestinal health [169].

The contribution of probiotics to host health occurs through strain-specific actions, including pathogen exclusion, immune modulation, and metabolic regulation—effects validated in both animal and human models [170]. Industry standards emphasize that these benefits should not be generalized and rigorous identification and stability during processing should take place to ensure product efficacy [165].

Approximately 80% of the more than 380 probiotic products marketed globally are dairy-based. Yogurt represents an effective delivery vehicle for probiotic strains. Diverse dairy matrices include milk, infant formulas, kefir, buttermilk, and butter, as well as various cheeses like cottage, white pickled, Cheddar, and Mozzarella. Simultaneously, non-dairy alternatives including soy-based yogurts, wheat and rice cereal matrices, and fruit or vegetable juices have been launched into the market. Fermented meats, chocolate, coffee brews, unpasteurized beer, and traditional beverages like African milk–maize blends constitute other innovative vehicles [171].

A randomized, double-blind, placebo-controlled study evaluated the effect of yogurt containing heat-treated *Lactiplantibacillus plantarum* OLL2712 on 148 prediabetic adults. Over 12 weeks of daily consumption, the OLL2712 group showed significantly greater reductions in HbA1c and glycoalbumin levels compared to the placebo group ($p < 0.05$). These improvements suggest that OLL2712-enriched yogurt effectively supports glycemic control and may reduce the risk of type 2 diabetes in at-risk populations [172]. Recent research on the effect of kefir grains compared to starter cultures on the viability of the probiotic *Lacticaseibacillus rhamnosus* GG (LGG) was reported. It was shown that natural kefir starter cultures serve as an effective matrix for the delivery of this probiotic strain without compromising the overall quality of the product [173]. Soy-based yogurts (using powder, isolate, and whey) and Danisco mixed probiotics significantly reduced fermentation time to 4 h, as reported recently [174].

Recent studies have highlighted the potential probiotic properties of *Limosilactobacillus fermentum*, including anti-inflammatory effects [175,176]. In this regard, a recent review by de Luna Freire et al. [177] highlights the potential of probiotic strains of *L. fermentum*, isolated from fruit-processing byproducts to promote host health and their potential application in the food industry. The reviewed studies showed that the administration of *L. fermentum* for 4 to 8 weeks promoted health benefits in rats, including antihypertensive, antioxidant, and anti-inflammatory effects, improved metabolic parameters, and modulation of the gut microbiota.

Recent genomic and bioinformatic advances have expanded the field toward next-generation probiotics (NGPs) and live biotherapeutic products (LBPs). NGPs are often identified through microbiota analysis for their role in managing inflammation and metabolic disorders [178]. *Akkermansia muciniphila*, *Faecalibacterium prausnitzii*, *Bacteroides* species, *Christensenella minuta*, certain *Clostridium*, *Streptococcus*, and *Enterococcus* species, the *Eggerthellaceae* family, *Parabacteroides goldsteinii*, *Pediococcus pentosaceus*, and *Prevotella copri*, are candidate NGPs [1].

Unlike traditional probiotics, NGPs are identified through bioinformatics and/or next-generation sequencing studies, have a well-defined mode of action and a broad spectrum of microbial genera and species, and show potential use as biotherapeutics to treat different clinical conditions [179].

It is postulated that NGPs could be used for the prevention and/or treatment of oxidative stress, inflammatory modulation and the prevention of neurodegenerative diseases, and regulation of the gut microbiome, among other potential uses. From a regulatory point of view, traditional probiotics typically follow established frameworks such as the FDA Generally Recognized as Safe (GRAS) designation or EFSA Qualified Presumption of Safety (QPS), often supported by a history of safe use. However, NGPs frequently require regulation as novel foods or live biotherapeutic products. This requires specific safety evidence for each strain, toxicological studies in accordance with new food regulations, genomic stability evaluation, antimicrobial resistance screenings, compliance with manufacturing quality standards, and robust preclinical and clinical validation [180]. Regulatory heterogeneity across jurisdictions remains a significant barrier to standardization and commercialization.

In vitro safety testing of potential new NGPs includes assessments of hemolytic activity, mucin and gelatin degradation, deoxyribonuclease presence, biogenic amine production, and antibiotic resistance. Polymerase chain reaction (PCR) is generally used to detect the corresponding marker genes.

Furthermore, evaluating the safety of NGPs is crucial, and simple animal models for screening are essential, as mammalian models are costly and raise ethical and safety concerns. Simple models, such as *Drosophila melanogaster*, *Caenorhabditis elegans*, and *zebrafish*, are increasingly used as preliminary, high-throughput screening tools to evaluate NGP safety and toxicity and host–microbiome interactions prior to mammalian studies [181].

7.2. Prebiotics in Fermented Foods

In addition to live microorganisms, fermented foods can also serve as sources of prebiotics. During fermentation, the transformation of complex carbohydrates and fibers in raw materials such as cereals, legumes, and vegetables into more accessible forms occurs that selectively lead to the growth of beneficial gut microbes occurs. Hence, the prebiotic potential of foods is enhanced by increasing the availability of oligosaccharides, resistant starches, and polysaccharide derivatives, which serve as key substrates for colonic fermentation [4,163]. Fermented grains, vegetables, and beverages like beer and wine, which provide glucans, polyphenols, and oligosaccharides, are such cases. Furthermore, the generation of certain prebiotics occurs in situ through the microbial metabolism; for instance, the synthesis of exopolysaccharides with prebiotic properties during the fermentation of dairy and cereal matrices [182]. Foods classified as 'synbiotic' need to exert a synergistic health benefit with clinical evidence [183].

7.3. Postbiotics in Fermented Foods

Postbiotics encompass a diverse range of non-viable microbial cells and cell components. They do not require viability to exert their effects, which may include antimicrobial activity, the modulation of immune function, and an influence on host metabolism. Fermented foods that undergo heat treatment or processing may still retain these beneficial compounds, thereby maintaining functional properties even in the absence of live microorganisms [184,185]. Postbiotics are considered safer than probiotics and easier to process and preserve [186]. They show numerous benefits in health maintenance, for example, in the prevention and treatment of celiac disease [187], in fertility enhancement [188], in the biodegradation of xenobiotics [189] and in the control and modulation of immune responses [190].

In this regard, Sawada et al. [191] evaluated the effect of a postbiotic on gastrointestinal function in a double-blind, placebo-controlled trial. The results showed that 3 weeks of consumption of a fermented milk-based beverage containing heat-inactivated *Lactobacillus gasseri* CP2305 significantly improved intestinal function, increasing stool frequency and stabilizing fecal consistency in individuals with constipation. Furthermore, an increase in SCFAs and modulation of the gut microbiota composition were observed in patients who received fermented milk containing the postbiotic.

The scope of postbiotic research has expanded to include acetic acid bacteria [192], *Phellinus linteus* [193], and *Phellinus baumii* [194], showing that non-probiotic postbiotics can enhance immune stimulatory activity beyond *Lactobacillus*. Additionally, plant-derived postbiotics have attracted interest. Zhao et al. [195] demonstrated that a reduction in immune organ damage in mice occurred through *Aspergillus niger*-fermented figs.

Basiodiomycetes such as *Ganoderma lucidum* BZ5, and daylilies fermented with that fungus in heat processing, provide a scientific basis for the development of novel functional foods with sinapinic acid and L-ergothioneine as the key bioactive constituents [196].

Enhanced antioxidant effects through bidirectional *Ganoderma lucidum* fermentation have been reported [197,198]. Kachrimanidou et al. [199] showed increased antioxidant properties after the fermentation of grape pomace and whey supernatant with *Ganoderma lucidum*.

Kwak et al. [200] explored the potential of *Limosilactobacillus fermentum* SPC L75-1 as a novel sourdough starter and investigated its effects on baking characteristics and postbiotic properties, and found it to be promising, with health benefits and potent antioxidant and anti-inflammatory activities.

Importantly, fermented foods create synergistic effects and contain a combination of these biotic components. The food matrix itself plays a critical role in the protection of bioactive compounds, the facilitation of their delivery, and the effects of their interaction with the host. This integrated perspective highlights fermented foods as sources of individual functional ingredients, but most specifically as dynamic systems capable of delivering multiple health-promoting factors simultaneously.

Fermented foods offer a promising and accessible dietary means to modulate the gut microbiome and support overall health as research continues to elucidate the mechanisms underlying the health effects of probiotics, prebiotics, and postbiotics. However, further studies are needed for the standardization of definitions, characterization of bioactive components, and establishment of clear links between specific fermented foods and health outcomes. Table 2 shows the mechanistic basis of fermented foods and their associated health effects.

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Table 2. Mechanistic basis of fermented foods and health effects.

Mechanisms		Microorganisms Involved	Health Outcome	Type of Study	References
Enzymatic transformation of raw substrates	Bacterial lactases in yogurt survive gastric acidity to digest lactose in the small intestine	*Lactobacillus delbrueckii* and *Streptococcus termophilus*	Improvement in lactose intolerance symptoms	RCT in humans and animals	[116]
	Reduction in FODMAPs	*Saccharomyces cerevisiae*	Long proofing (>4 h) reduces wheat bread FODMAPs by up to 90%	In vitro	[117,118]
	Elimination of antinutritional factors	LAB, *Bacillus*, *Saccharomyces*	Increased availability and digestibility of nutrients	In vitro	[120,130]
	Release of enzymes such as glucosidases and decarboxylases, which break down the cell walls of plants and glycosidic bonds	LAB strains	Increased bioavailability of phenolic compounds and antioxidants	In vitro	[131,132]
Biosynthesis of bioactive metabolites	B12 vitamin	*Limosilactobacillus reuteri* CRL 1098	Fermented soy milk prevented the development of symptoms of nutritional vitamin B12 deficiency	RCT in female mice and their offspring	[136]
	B2 vitamin	LAB strains	Increased folate status	In vitro and RCT in rats and humans	[133,135]
	K vitamin	*Bacillus subtilis* var. *Natto*, LAB strains, *Flavobacterium meningosepticum*	Blood clotting, bone health, and prevention of cardiovascular disease	RCT in humans and animals	[134]
	Gamma-aminobutyric acid	LAB strains, *Bifidobacterium*, *Rhodotorula*, *Neurospora crassa*, *Aspergillus nidulans* and *Aspergillus niger*, *Monascus* spp., *Saccharomyces*, *Candida* spp.	Increased GABA concentration. Reduced the excitability of specific sensory neurons in the colon.	In vitro and RCT in animals	[11,139,140]
	Exopolysaccharides	LAB strains	Antioxidants, barriers against pathogens, and hypocholesterolemic activities	In vitro and RCT in animals	[7,137,138]
	Short-chain fatty acids	LAB strains, *Bifidobacterium* and yeast	Regulating intestinal barrier integrity and modulating immune response	In vitro and RCT in animals	[143–151]
Modulation of the gut microbiota	Restore microbiota diversity	LAB strains, Bifidobacterium, molds and yeast	Microbial diversity and the abundance of beneficial bacteria	RCT in animals and humans	[10,154,155]
	Vehicles of probiotics	Traditional probiotic (mainly LAB and *Bifidobacterium*) and NGP (*Akkermansia muciniphila*, *Faecalibacterium prausnitzii*, *Bacteroides* species, *Christensenella minuta*, certain *Clostridium*, among others)	Pathogen exclusion, immune modulation, and metabolic regulation	RCT in animals and humans	[172–177]
	Vehicles of postbiotics	LAB strains, *Phellinus linteus*, *Phellinus baumii*, *Ganoderma lucidum*	Treatment of celiac disease, biodegradation of xenobiotics, modulation of immune response, improved intestinal function, antioxidant and anti-inflammatory activities		[187–200]

8. Safety and Regulatory Considerations in Fermented Foods

The growing expansion of functional fermented food consumption and microbiome-based interventions necessitates attention to food safety and appropriate regulatory frameworks [201]. Traditionally, fermented foods have been considered safe because fermentation produces antimicrobial metabolites such as acids and bacteriocins that can inhibit potential pathogens, as well as spoilage microorganisms. However, inadequate hygiene and fermentation practices, along with the use of unsafe microorganisms, can lead to the accumulation of toxic metabolites such as biogenic amines and mycotoxins, or the proliferation of microorganisms that pose a health risk [202]. Furthermore, special attention must be paid to the regulatory framework for the incorporation of novel microbial strains with no history of safe use, as well as genetically modified microorganisms. Consequently, ensuring microbial safety, strain traceability, contamination control, and regulatory clarity has become essential for the development and marketing of fermented products.

8.1. Selection of Safe Strains

Selecting safe starter cultures requires ensuring that the microorganisms are suitable, stable, and non-pathogenic. Strains must be classified as GRAS or achieve QPS status from the EFSA. To achieve this, the safety of the microorganisms must be assessed at both the taxonomic and strain-specific levels [203]. The presence of virulence factors, toxin production, and antimicrobial resistance traits often vary among strains of the same species. Therefore, a comprehensive safety assessment includes taxonomic identification, evaluation of toxigenic potential, characterization of virulence determinants, antimicrobial resistance profiling, and examination of metabolic activities that may generate undesirable compounds, such as biogenic amines or toxic metabolites [202].

8.2. Contamination Risks in Fermented Foods

Although fermentation generally inhibits the growth of pathogens through the production of inhibitory metabolites and competition, contamination, especially in traditional fermented products, is a current concern. Sources of contamination include raw materials, environmental exposure, processing equipment, packaging materials, and starter cultures [202].

Fermented foods particularly susceptible to microbial contamination include meat and dairy products, cereals, and fermented fruits and vegetables such as sauerkraut and kimchi. Between 2018 and 2022, fermented foods were responsible for 1.2% of foodborne illness outbreaks in the EU, according to the European Food Safety Authority (EFSA) [204].

Potential microbial risks include foodborne pathogens such as *Listeria monocytogenes*, *Salmonella* spp., enteropathogenic *Escherichia coli*, and *Staphylococcus aureus* [205]. Furthermore, spoilage microorganisms, such as molds and yeasts, can negatively affect product quality and safety. Additionally, the growth of contaminating microbes can be associated with the production of toxic metabolites such as mycotoxins and biogenic amines. Finally, fermented foods, especially those produced by spontaneous fermentation, can be potential reservoirs of antimicrobial resistance genes. While in laboratory settings, for example, these resistance traits are intrinsic, horizontal transfer could pose a potential risk [206].

These health risks highlight the need to improve fermentation techniques and establish strict safety standards to mitigate these hazards. The implementation of Hazard Analysis and Critical Control Points (HACCP) systems, Good Manufacturing Practices (GMP), environmental monitoring programs, and genomic surveillance approaches is increasingly important to ensure the microbiological safety and quality of fermented products.

8.3. Authentication and Traceability in Fermented Products

Food labeling can sometimes be manipulated or falsified to gain greater financial benefit, thus constituting food fraud. Therefore, food authentication and strain traceability represent a critical component of food safety in modern fermented foods [207].

Each fermented food and beverage is characterized by a unique microbiota originating from the starter cultures, raw materials, equipment, and processing environment. The composition and evolution of these microbial consortia determine the technological quality as well as the sensory attributes of the final product [208]. Historically, phenotypic methods and biochemical characterization were used for strain identification; however, these approaches often lack sufficient resolution to distinguish between specific related microorganisms. Currently, authentication and traceability are increasingly based on molecular tools, such as WGS, metagenomic sequencing, and strain-specific molecular markers, among others [209,210].

Distinctive microbial fingerprints specific to the geographical area of origin are used as authenticity markers for fermented foods and beverages with Protected Designation of Origin (PDO) and Protected Geographical Indication (PGI) status [208]. Specific biomarkers can be used for starter or adjunct cultures to authenticate fermented foods and beverages. In the specific case of probiotic foods and beverages, it is also mandatory to quantify each probiotic listed on the label. In these cases, accurate strain-tracking is particularly relevant, as efficacy claims depend on the presence of specific, validated strains [211].

8.4. Regulatory Concerns

Global regulatory frameworks for fermented foods remain highly heterogeneous, with most regulations emphasizing food safety, labeling, composition standards, and manufacturing practices rather than functional or health attributes. International guidelines are generally framed within the Codex Alimentarius, a collection of standards, guidelines, and codes of practice [201]. However, fermented foods are not widely represented in the Codex Alimentarius. The fourth revision of the Codex Alimentarius Standards for Fermented Milks, published in 2018, standardizes guidelines for yogurt and other fermented or cultured dairy products, such as acidophilus milk, kefir, and kumis.

Regulatory classification varies across jurisdictions, where products may be categorized as functional foods, novel foods, or probiotic-containing products. This lack of harmonization poses challenges for health claims and marketing authorization, underscoring the need for globally standardized regulatory frameworks.

9. Precision Fermentation

Precision fermentation is the utilization of engineered microorganisms to produce identical dairy proteins (like casein and whey) without the involvement of animal agriculture.

AI-driven precision fermentation, where CRISPR-based microbial optimization and reinforcement learning accelerate bioactive compound synthesis, has been discussed by Priyadharshini et al. [212]. AI enables scalable and sustainable alternatives to resource-intensive agricultural practices through the optimization of microbial strain design, bioreactor dynamics, and synthesis pathways. AI accelerates CRISPR-based microbial design through the prediction of gene-editing. For example, *Saccharomyces cerevisiae* transcriptomic data from deep learning models show promoter–gene pairs that boost alt-protein yields by 300% [213].

Bioreactor systems are optimized by reinforcement learning (RL) algorithms, hence dynamically adjusting parameters (e.g., temperature, pH) in real-time and enhancing metabolite yield in precision fermentation [66].

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AI-Driven Culture Optimization and Fermented Foods

Food contamination, expiration risks, and harmful components can be monitored in real-time by AI through image recognition, sensor data analysis, and predictive modeling, hence leading to improvements in traceability and supervision efficiency [214–216].

Machine learning (ML)-driven analysis in fermentation and microbial research relies on genomic and metagenomic data from next-generation sequencing, revealing microbial diversity, functional pathways, and evolutionary relationships [217]. ML broadly consists of supervised learning, unsupervised learning, and semi-supervised learning [218–220]. ML is exemplified by random forest (RF) and support vector machine (SVM), which are traditional algorithms. Deep learning (DL), a specialized subset of ML, refers to deep neural network algorithms, such as convolutional neural networks (CNNs) and recurrent neural networks (RNNs).

Specialized databases such as the curated Food Metagenomic Data (cFMD) resource cover traditional fermentation microorganisms [221]. Amplicon datasets from 108 studies, encompassing 4710 microbial taxa across 62 food types, are included in FoodMicroDB [222] and the Fermented Dairy Food Database (FDF-DB) includes data on traditional fermented dairy products [223].

Atta et al. [224] also looked at AI-driven methodologies and optimization techniques for enzyme activation and found that fungal enzyme activity significantly increases with co-culture and co-fermentation techniques.

AI-driven protein design, precision fermentation, and circular bioeconomy frameworks offer pathways for overcoming limitations in culture meat products and insect proteins [225].

The integration of mechanistic metabolic models with data-driven methods is being explored to refine fermentation parameters [226,227].

10. Conclusions

Fermenting foods is one of the oldest and most enduring practices in the human diet. Improved food safety and extended shelf life through fermentation played a fundamental role in the survival of early human populations. Beyond these benefits, fermentation increases nutritional value, generates bioactive compounds, modulates the composition of the gut microbiota, and serves as a vehicle for beneficial live microorganisms.

The global production of more than 5000 varieties of fermented foods reflects their enormous gastronomic, economic, and cultural importance. However, the transition to industrialization and large-scale production has prioritized standardized manufacturing and microbiological stability, often at the expense of nutritional value, microbial diversity, and sensory characteristics. This trend may have health impacts that we are only beginning to understand. The challenge is to preserve microbial and cultural heritage without compromising modern demands for rigorous food quality and safety standards, ensuring that diversity and tradition can coexist with the highest levels of consumer protection.

It also needs to be stressed that industrialization may reduce microbial diversity in some cases, but it can also improve safety, consistency, traceability, and quality control.

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