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EXPLORING THE RICHNESS OF INDONESIAN FERMENTED FOODS: PRESERVATION, NUTRITION, AND HEALTH BENEFITS

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KEYWORDS:
Indonesian fermented food, fungi, lactic acid bacteria, traditional foods

ABSTRACT

Fermentation is an ancient preservation method that can improve the nutritional profile of food. This method enhances the organoleptic characteristics and shelf life of food. The use of microorganisms has become a pillar of cultural identity and technological advancement in food, resulting in highly nutritious foods such as peyeum, brem, terasi, tauco, dadih, tape ketan, oncom, and acar. This review study aims to present a comprehensive and in-depth data of the variety of traditional fermented foods found across the Indonesian archipelago. This review will systematically explore the practice of food fermentation in Indonesia. It will cover the local raw materials used, production methods passed down from generation to generation, the role of microbes in improving nutritional quality, and the taxonomic identification of lactic acid bacteria and fungi involved in the fermentation process of these traditional foods. In addition, the nutritional content and potential health benefits will also be analyzed in this review. Through extensive literature review, this study seeks to summarize and synthesize the existing knowledge regarding the richness and uniqueness of Indonesian fermented foods. In the face of globalization that threatens culinary diversity, a deep understanding and efforts to preserve traditional fermentation practices have become increasingly urgent. Such actions are not only crucial to protect invaluable culinary heritage from potential degradation but also plays a vital role as a supporting instrument to meet nutritional needs of the community sustainably and potentially empowering local economic growth through the optimal utilization of abundant food resources in various regions.

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АНАЛИЗ ИЗОБИЛИЯ ИНДОНЕЗИЙСКИХ ФЕРМЕНТИРОВАННЫХ ПРОДУКТОВ: ХРАНЕНИЕ, ПИТАНИЕ И ПОЛЬЗА ДЛЯ ЗДОРОВЬЯ

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КЛЮЧЕВЫЕ СЛОВА:
индонезийские ферментированные пищевые продукты, грибы, молочнокислые бактерии, традиционные пищевые продукты

АННОТАЦИЯ

Ферментация — метод сохранения пищевых продуктов, используемый с древних времен, может существенно продлить срок годности и повысить ценность различных традиционных индонезийских пищевых продуктов с большим разнообразием вкусов и культурных традиций, таких как пейеум, брем, тераси, тауко, дадих, кекап манис, тапе кетан, онком и акар. Целью данного исследования было предоставление исчерпывающих и глубоких данных по разнообразию традиционных ферментированных пищевых продуктов, которые встречаются на всём индонезийском архипелаге. В данной работе детально изучается историческое происхождение, разнообразие используемого местного сырья, стадии производства, которые часто передаются от поколения к поколению, важная роль различных типов микроорганизмов в трансформации пищевых продуктов, идентификация и значение молочнокислых бактерий и грибов, которые вносят вклад в уникальные характеристики продуктов, а также подчеркиваются высокое содержание пищевых веществ и потенциальная польза для здоровья от потребления этих традиционных ферментированных продуктов. На основе обзора обширной литературы, в данном исследовании обобщены существующие знания об изобилии и уникальности индонезийских ферментированных продуктов. В условиях глобализации, которая угрожает кулинарному разнообразию, глубокое понимание и усилия по сохранению традиционных практик приготовления ферментированных пищевых продуктов становятся всё более насущными. Такие действия

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не только критически важны для защиты бесценного кулинарного наследия от угрозы исчезновения, но также играют важную роль в соответствии потребностям в пищевых веществах, обладая потенциалом поддержки экономического роста местных сообществ экологически рациональным образом в результате оптимального использования обильных пищевых ресурсов в разных регионах.

ФИНАНСИРОВАНИЕ: Авторы выражают свою благодарность Паджаджаранскому университету за финансирование этого исследования в рамках гранта на развитие Внутренней Исследовательской Компетентности Преподавателей Unpad (RKDU) (грант № 4580 / UN6.D / PT.00/2025).

1. Introduction

Indonesia, as a tropical archipelago with abundant biodiversity. These geographical conditions play a crucial role in various local agricultural activities. The agricultural sector not only plays a role in supporting national food security, but also contributes significantly to the economic structure, the livelihoods of the community, and national identity [1]. One of the outcomes of Indonesia's agricultural system is the emergence of diverse food processing techniques tailored to the country's climate conditions and local resources. Among these techniques is fermentation, which functions as a vital food preservation method in cultural and economic contexts [2]. Fermentation has evolved as a sustainable and economical preservation methods that contribute to increased nutrient bioavailability, extended food shelf life, and enhanced food safety [3]. Fermentation is a food preservation solution, especially for areas with limited access to refrigeration technology. Microorganism activity, such as lactic acid bacteria and mold in foods like tempeh, contributes positively to food shelf life [4].The diversity of fermented foods in Indonesia reflects the cultural and ecological richness of each region. The raw materials, fermentation techniques, and types of microorganisms used vary widely from one area to another [5,6]. Figure 1 illustrates the distribution of fermented foods across the Indonesian archipelago, highlighting local adaptations to available resources.

Scientifically, fermentation is a biochemical process involving controlled microbial activity, resulting in changes in food composition through enzymatic reactions [7]. This process not only modifies the taste and texture of food but also enhances nutritional content and improves food safety. One of the primary mechanisms is the production of lactic acid by LAB, which lowers the pH and creates an environment unfavorable for pathogens [8]. The interaction between various microorganisms, such as fungi, bacteria, and yeasts, contributes to the production of complex fermented products with rich nutritional benefits [9]. Microorganisms involved in Indonesian food fermentation include various bacterial species such as *Leuconostoc mesenteroides*, *Lactiplantibacillus plantarum*, *Limosilactobacillus fermentum*, and *Lacticaseibacillus rhamnosus* [10–12]. On the other hand, fungi like *Rhizopus oligosporus* and *Aspergillus oryzae* play important roles in products such as tempeh and soy sauce [13]. With growing global attention on the health benefits of fermented foods, Indonesian fermented products are beginning to gain international recognition, particularly due to their probiotic content, which supports digestive health, immunity, and food system sustainability [7]. However, systematic studies comparing the microbiological composition, fermentation dynamics, and functional metabolites of Indonesian fermented foods are still lacking, especially in relation to their health-promoting properties and safety profiles.

Despite their immense potential, traditional Indonesian fermented foods face serious threats from modernization and shifts in consumption patterns [14]. This creates an urgent need to document, preserve, and further study the diversity of local fermentation techniques and the associated microbiota. Research on traditional Indonesian fermentation microbes, particularly their health benefits, remains relatively limited compared to similar studies in other countries [5]. Through this review, we aim to systematically explore the richness of Indonesian fermented foods by highlighting their historical origins, raw materials, fermentation techniques, key microorganisms involved, as well as their nutritional and health benefits. Additionally, this review seeks to bridge traditional knowledge with scientific perspectives, identify research gaps, and promote the preservation and global recognition of Indonesia's diverse culinary heritage.

2. Objects and methods

This article was compiled using a descriptive literature review approach to explore the diversity of Indonesian fermented foods from the aspects of preservation, nutritional content, and health benefits. This review is based on a comprehensive literature synthesis conducted on

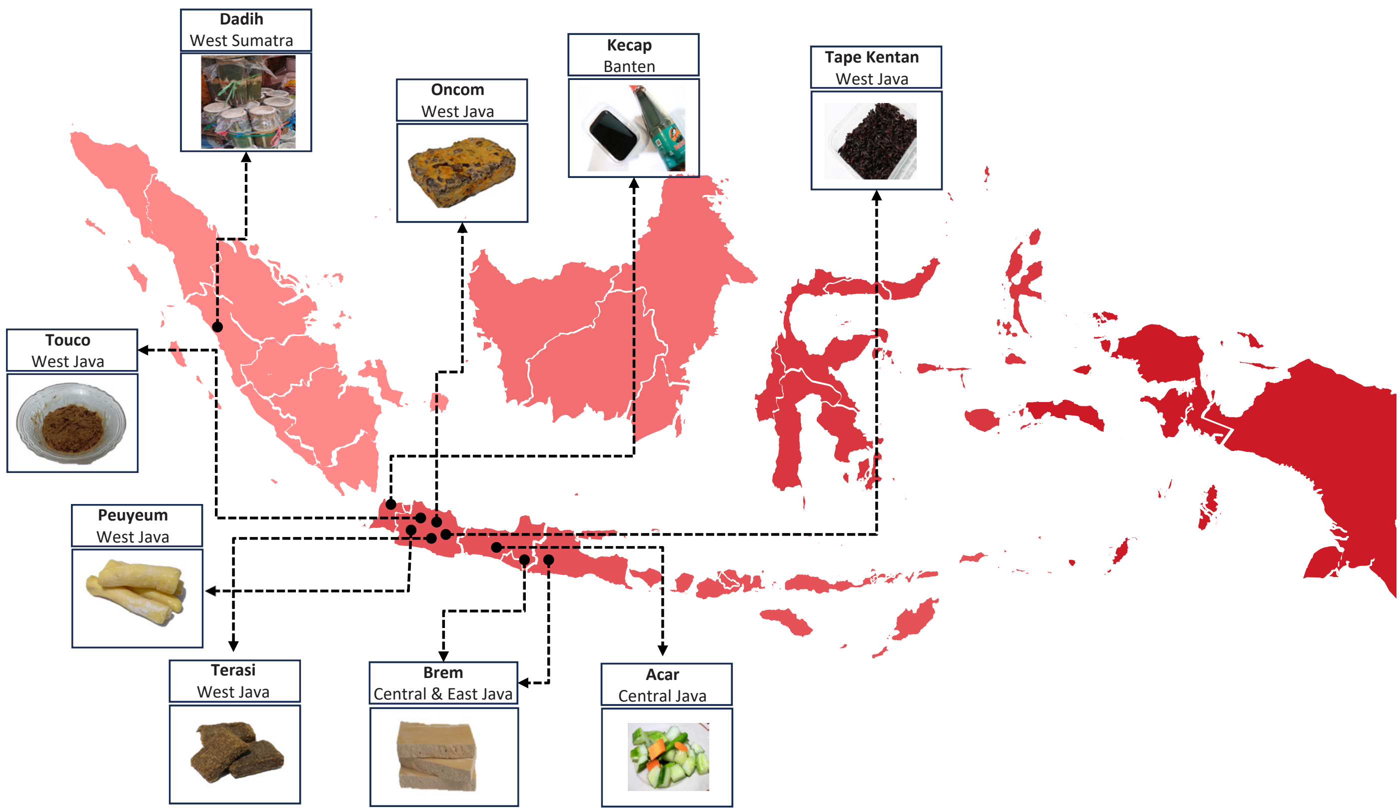

Figure 1. **Map of the distribution of Indonesian fermented foods**
Рисунок 1. **Карта распространения индонезийских ферментированных пищевых продуктов**

leading journal platforms such as Google Scholar, PubMed, ScienceDirect, and Scopus. The inclusion criteria for selecting reference sources include:

- Articles are primary research or review articles that have been indexed.
- Focus on Indonesian fermented food products or similar foods from other countries that are biologically and culturally relevant.
- Articles containing discussions on preservation mechanisms, nutritional value, and potential health benefits.
- Articles published within the last 10 years (2014–2024) to ensure data currency.

Selected articles were descriptively analyzed to identify patterns, trends, and scientific contributions to the understanding of the role of fermented foods in food systems and public health. The search was not limited to studies originating from Indonesia but also included relevant international literature that supports and explains the potential of Indonesian fermented foods in a global context.

3. Indonesian food fermentation and the manufacturing process

3.1. Tapai Singkong and Peuyeum

Indonesia is a nation known for the cultivation of root crops, such as potatoes, taro, sweet potatoes, and cassava [15]. Cassava (*Manihot esculenta*) is extensively subjected to fermentation using yeast (*Saccharomyces cerevisiae*), resulting in the production of tapai singkong and peuyeum. These traditional fermented delicacies have obtained considerable popularity after tempeh [16]. Tapai Singkong is available across various regions of Indonesia, while peuyeum is a distinctive specialty of Bandung. In general, peuyeum serves as a souvenir representing Bandung for tourists and is also a staple in the daily diet of the local community [3].

Tapai singkong and peuyeum are traditional fermented products made from cassava with notable similarities, yet distinct production methods and textures. Tapai singkong is prepared by peeling, washing, and steaming cassava until partially cooked, followed by inoculation with a small amount of yeast and fermentation for approximately 72 hours under semi-anaerobic conditions, resulting in a soft texture [17]. In contrast, peuyeum involves peeling and half-boiling the cassava, then fermenting it with a higher yeast concentration under anaerobic conditions for the same duration, producing a firmer texture [16,18].

Typically, peuyeum retains the shape of the whole cassava and exhibits a yellowish-white coloration [3], as seen in Figure 2. Furthermore, peuyeum can be processed into various derivative products, including colenak (grilled fermented cassava served with coconut sugar sauce), fried peuyeum, fermented cassava cakes, and mixed ice desserts, all of which are widely consumed across Indonesia [15]. The taste of fermented tapai singkong and peuyeum becomes sour due to the metabolic processes of yeast and bacteria during fermentation [19]. During fermentation, glucose is converted into ethanol and carbon dioxide by yeast. Simultaneously, bacteria convert some of the alcohol into organic acids such as acetic acid, contributing to the sour taste [20]. The packaging of tapai singkong or peuyeum during fermentation can also affect the taste. Tapai singkong wrapped in plastic will taste sourer, while tapai singkong wrapped in banana leaves will taste sweeter due to the natural properties of banana leaves [21]

3.2. Brem

Solid brem is a traditional fermented product made from glutinous rice, originating from Madiun and Wonogiri (Figure 3) [22]. It is produced from glutinous rice extract and is characterized by a sweet-sour taste and a floury texture, commonly consumed as a snack. Solid brem is available in two color variants: solid white and yellowish-white [23]. The fermentation process involves the presence of fungi such as *Saccharomycopsis fibuligera* and *Wickerhamomyces anomalus* [24].

In addition to the solid form, liquid brem is another traditional fermented glutinous rice product, commonly found in Bali. It remains widely known and produced, playing an important cultural role in religious ceremonies and traditional medicine [25]. Liquid brem is made by fermenting steamed glutinous rice sprinkled with tape yeast (ragi tape) for five days at room temperature (27 °C), producing fermented rice known as tape. The tape is then pressed to extract the juice, which is subsequently fermented for six months in a sealed container or fermentation tank [26].

3.3. Terasi

Terasi is a fermented food product commonly used as a spice and culinary accompaniment in Indonesia. This condiment has its origins in the island of Java and is primarily crafted from a mixture of shrimp and fish, typically presented in a paste-like form, as seen in Figure 4. The effectiveness as a flavor enhancer can be attributed to the substantial glutamate content. Across numerous Asian countries, this food is used as a seasoning agent in cooking, as evidenced by the various regional names and utilization. Some of the countries where terasi is consumed and referred to by distinct names include Thailand (*kapi*), Cambodia (*Belacan*), Malaysia (*Mamrouc*), Brunei (*Mamtom*), Myanmar (*Ngapi*), China (*Shajiang*), and Korea (*Saewoojeot*) [27].

Terasi, or shrimp paste, is produced from fundamental components including shrimp (*Acetes japonicus*), sugar, salt, and water [28]. The preparation includes boiling raw or planktonic prawns in water for approximately 5 minutes. These boiled shrimps are drained before adding 15 % salt (comprising 15 grams of salt per 100 grams of shrimp) and the fermentation process is executed in two phases. The initial step includes fermenting the salted shrimp within a sealed container for a period of two days at approximately 25 °C. Subsequently, the shrimp paste is blended using a blender and manually formed into flat balls measuring 8–10 centimeters in diameter, resembling pasta. To reduce water content, the paste is subjected to a drying process in an oven for 4 hours at 50 °C. The phase comprises a second round of fermentation, with the paste left to ferment for a duration of 1–3 months [29]. Terasi shows a solid, paste-like consistency with a coarse texture and a moderately strong aroma [27].

3.4. Tauco (Taoetjo)

Tauco is a traditional Chinese food introduced to Indonesia many centuries ago. This food gained prominence in Cianjur, West Java Province, and subsequently spread across the coastal regions [30]. In Indonesia, tauco has been widely used as a culinary spice due to its delightful umami or savory flavor. The fundamental ingredient for producing tauco is soybean seeds (*Glycine max*) (Figure 5). Tauco comes in three distinct forms, namely solid, semi-solid, and liquid with varying moisture content. The nutritional content of 100 grams of touco is presented in Table 1. These soybean seeds are boiled, mashed, blended with wheat flour, and subjected to fermentation. The fermented tauco is immersed in a saltwater solution and exposed to the sun's heat for several weeks before developing a distinctive aroma [31].

The fermentation process includes the growth of fungi and/or bacteria, lasting for a period of 3–6 days, with the assistance of the addition of *Aspergillus oryzae* or *Aspergillus sojae*. During this fermentation, various enzymes are generated, namely protease, amylase, and lipase [31]. The proteolytic enzymes produced by *A. oryzae* can hydrolyze soybean proteins into smaller peptides and free amino acids. This hydrolysis process is crucial for the development of the characteristic umami flavor in tauco, particularly through the release of glutamic acid, which provides a savory taste [32, 33]. In addition to producing proteolytic enzymes, *A. oryzae* also produces amylolytic enzymes that function to hydrolyze soybean starch into simple sugars. This hydrolysis process not only enhances the product's flavor but also increases nutrient availability and digestibility of the final product [34].

Figure 2. **Peuyeum, a fermented cassava from West Java**
Рисунок 2. **Пейеум — ферментированная кассава с Западной Явы**

Figure 3. **Brem, a traditional fermented food originating from Madiun**
Рисунок 3. **Брем — традиционный ферментированный пищевой продукт, происходящий из Мадиуна**

Figure 4. **Terasi as a spice and culinary accompaniment in Indonesia**
Рисунок 4. **Тераси как специя и кулинарное дополнение в Индонезии**

3.5. Oncom

Oncom is a traditional Indonesian fermented food originating from West Java [35]. It is primarily produced using agricultural by-products such as tofu dregs, cassava fiber (onggok) and groundnut cake (Figure 6). For decades, oncom has served as a valuable source of affordable nutrition due to its unique flavor and meat-like texture [36]. Oncom is available in two main varieties: red oncom (oncom merah), fermented using *Neurospora sitophila*, and black oncom (oncom hitam), fermented with *Rhizopus microsporus* var. *oligosporus* [37]. The production process involves soaking tofu dregs, groundnut cake and cassava fiber (onggok) for 3–4 hours and 1 hour, respectively. These components are then combined, molded into thin layers, and boiled for 1 hour. After cooling, the mixture is inoculated with oncom starter culture and placed into bamboo containers lined with banana leaves. Fermentation occurs at ambient temperatures (25–30 °C) over 36–48 hours [37]. Nutritional profiles of red and black oncom are detailed in Table 1.

R. oligosporus plays a functional role by producing α-galactosidase, an enzyme that degrades gas-producing oligosaccharides in legumes, thereby reducing the risk of flatulence. Moreover, fungi used in the fermentation of oncom and tempeh have been shown to suppress the growth of aflatoxin-producing molds such as *Aspergillus flavus* [38]. Fermentation with *R. oligosporus* also enhances the protein content of oncom and significantly reduces antinutritional compounds such as phytates by 34–58 % [39]. In Indonesia, oncom is classified into four quality grades based on the raw materials used in production [40]: 1) super-class oncom — the highest quality, often sold in supermarkets or designated for export. 2) first-class oncom — slightly lower in quality but still considered premium, commonly found in local markets (Figure 6). 3) second-class oncom — a widely consumed variety, typically sold in traditional markets. 4) third-class oncom — the lowest grade, generally used as an ingredient in seasoning blends or cooking spices [39].

3.6. Dadih

Dadih is a traditional yogurt made from buffalo milk, fermented inside bamboo containers sealed with plastic or banana leaves, as seen in Figure 7. This time-honored practice has been carried out by the Minangkabau people of West Sumatra, for centuries. The resulting fermented product is similar to yogurt, featuring a smooth and glossy texture, creamy color, pleasant aroma, and a tangy [40]. Buffalo milk is subjected to a natural fermentation process within bamboo containers at ambient temperatures of 25–30 °C for approximately 3 days [41,42]. Analysis has shown that dadih contains approximately 82.10 % water, 8.08 % fat, 6.99 % protein, and 5.29 % lactose, as well as 13 essential amino acids, 3 non-essential amino acids, and 70 IU/gram of vitamin A [43].

Traditional dadih fermentation involves a complex interplay of various microorganisms. These microorganisms, thought to originate from the inner bamboo surface, covering leaves, and the milk itself [44], play a crucial role in the fermentation process. The fermentation of carbohydrates, influenced by proteolytic and lipid metabolism, significantly contributes to the development of structure and flavor of dadih. Carbohydrate metabolism is inextricably linked to the enzymatic activity of lactic acid bacteria can facilitate the conversion of lactose into lactic acid via the β-galactosidase pathway and lactic acid fermentation [45].

3.7. Kecap Manis

Soy sauce is a fermented product widely utilized as a flavoring agent. A distinctive characteristic of Indonesian soy sauce (Figure 8), differentiating it from those in other countries, is the prevalence of sweet soy sauce [46]. Soybeans serve as the primary ingredient in soy sauce production and possess a notably high protein content [47].

There are two types of fermentation methods used in the production of soy sauce, namely liquid and solid fermentation, also known as moromi and koji/tempeh fermentation. Solid fermentation typically takes 3–5 days; the outcome is referred to as "koji/tempeh" and "tempeh" when *Aspergillus* sp. and *Rhizopus* sp. are used as the fermenting agent. Conversely, moromi fermentation spans a period of 14–28 days and in this process, the koji/tempeh is dried before soaking in a 20–30 % saltwater solution.

A. oryzae is a fungal species commonly used in soy sauce fermentation, particularly in the production of koji. During koji fermentation, the biochemical transformation facilitated by *A. oryzae* includes the breakdown of complexes such as protein, lipid, and carbohydrate hydrolysis [48]. Various essential enzymes are produced by *A. oryzae* during the fermentation process. Starch broken down into simple sugars by amylase enzymes serves as an energy source for the fermentation process. The umami flavor produced in soy sauce fermentation is generated by amino acids derived from proteins hydrolyzed by protease enzymes [49]. The overall final flavor profile of soy sauce is influenced by the micromolecules formed during fermentation.

3.8. Tape Ketan

Tape ketan is a fermented food made from glutinous or sticky rice, subjected to fermentation using *S. cerevisiae* [50]. The food product has a soft texture with a high moisture content and a sweet taste [51], as seen in Figure 9. Moreover, sticky rice tape is a commonly consumed food in Indonesia and the traditional method of preparation includes several

Figure 5. **Tauco from Cianjur is available for sale in grocery stores**
Рисунок 5. **Тауко из Чианджур продается в бакалейных магазинах**

Figure 6. **Red oncom is produced using groundnut cake**
Рисунок 6. **Красный онком изготавливается, используя арахисовый жмых**

Figure 7. **Dadih is a traditional yogurt made by fermenting buffalo milk inside bamboo containers, which are covered with plastic**
Рисунок 7. **Дадих — традиционный йогурт, изготавливаемый путём ферментации молока буйволов внутри бамбуковых ёмкостей, которые покрываются пластиком**

Figure 8. **Soy sauce is fermented by *Aspergillus* sp.**
Рисунок 8. **Соевый соус, ферментированный *Aspergillus* sp.**

Figure 9. **Black Tape Ketan without banana leaf wrapping**
Рисунок 9. **Чёрный тапе кетан без обертывания банановыми листьями**

steps. Sticky rice is cleaned to remove its husk, weighed to about 0.5 kg, and steamed for 2 hours using 2 liters of distilled water. After 2 hours, the steamed sticky rice is allowed to cool until the temperature reaches 25 °C. The rice is mixed with yeast and stirred until the content is evenly distributed. Subsequently, it is wrapped in banana leaves and left to ferment for 48–72 hours [52].

During tape fermentation, microorganisms metabolize the nutrient compounds in glutinous rice. Yeast hydrolyzes starch into simple sugars, which are then fermented to produce alcohol and the characteristic aroma of tape [53]. Tape Ketan is served as a dessert, offering a sweet taste with sour organoleptic characteristics and having a moderate alcohol content [14]. Tapai ketan contained 0.51–0.67 % alcohol with 0.5–1.5 % *S. cerevisiae* [54]. The nutritional compound content in sticky rice tape is shown in Table 1. Black Tape Ketan (sticky rice) contains a high level of anthocyanins, which offer health benefits such as reducing the risk of colon cancer. Anthocyanins also possess the capability to inhibit the damage caused by free radicals, including cancer cells [55].

3.9. Acar

Acar pickles are preserved foods made from vegetables or fruits, including cucumbers, carrots, chili, and onions, combined with salt and vinegar, as seen in Figure 10. Additionally, sugar or other spices can be added for seasoning [56]. Acar pickles are a well-known accompaniment in Indonesian cuisine, often served with dishes like satay, fried noodles or rice, and soto. To prepare this food product, carrots, cucumbers, chili, and onions are cut into uniform sizes and placed in a jar. A brine is prepared by boiling a mixture of water, vinegar, sugar, and salt. In addition, the hot brine is poured into the jar, which is left open for 1 hour. The jar is sealed and refrigerated for three days to a week. The longer the marination period, the better the taste [57].

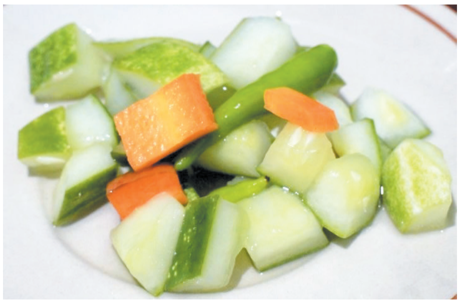

Figure 10. **Acar, a mixture of cucumber, carrot, chili, onion and brine solution**
Рисунок 10. **Акар — смесь огурцов, моркови, чили, лука и рассола**

4. Role of fungi in Indonesian fermented food

Fermentative microorganisms offer a unique approach to food stability through physical and biochemical changes in fermented foods [8]. One important group of microorganisms involved is fungi. During fermentation, fungi interact with other microorganisms, such as bacteria and yeasts, through nutrient competition, the production of antimicrobial compounds, and facilitating the growth of specific microbes. This complex interaction directly influences the characteristics of the final product, particularly in terms of taste and texture [58]. The activity of antimicrobial compounds ensures food safety by preventing spoilage and inhibiting the growth of harmful pathogens [59]. For example, certain fungal species produce secondary metabolites, such as organic acids and antibiotics, which contribute to the safety and durability of fermented products. This role becomes particularly significant in traditional fermentation practices [60].

Beyond their contribution to food preservation, fungi also offer substantial benefits in food biotechnology through their rich nutritional profile. This advantage contributes to cost efficiency in the food industry, enabling the production of high-quality foods on a large scale at lower costs [61]. Furthermore, fungi play a role in breaking down complex carbohydrates, proteins, and fats during the fermentation process, thereby improving digestibility and nutrient bioavailability [62]. The fermentation of soybeans into tempeh, *R. oligosporus* not only develops the characteristic texture and organoleptic profile, but fermentation also contributes to facilitating product bio-enrichment through increased biosynthesis of vitamin B, including folic acid, nicotinamide, niacin, pyridoxine, and riboflavin [63]. In addition to improving nutritional value, the microorganisms involved in fermentation also contribute to the degradation of antinutritional factors commonly found in food ingredients. This degradation process eliminates the toxic properties of these compounds and enhances food safety, making previously fewer consumable substrates safe for consumption [14]. This highlights the crucial role of these microorganisms in improving both nutrition and food safety. The role of various fungal species in Indonesian fermented foods is summarized in Table 1.

5. Characterization of Lactic Acid Bacteria: Microbial diversity and functional role in health

Lactic acid bacteria are microbes composed of a thick layer of peptidoglycan, and are therefore classified as gram-positive bacteria. This heterogeneous group of microorganisms includes various major genera such as *Lactobacillus, Pediococcus, Streptococcus, Leuconostoc*, and *Enterococcus* [71]. The diversity of LAB encompasses differences in acid tolerance, substrate preferences, and the ability to produce bioactive metabolites, enabling them to adapt to various fermented food matrices, ranging from dairy products to fermented vegetables. Each LAB species possesses specific functional characteristics, such as the production of antimicrobial compounds, enhancement of nutritional value, and contributions to the sensory characteristics of fermented products [72]. This variation forms the basis for selecting LAB strains for applications in the food and health industries.

Fermented foods containing LAB offer significant health benefits. This is due to the presence of probiotics that help maintain gut flora balance, as well as bioactive compounds produced during fermentation, which have various positive effects on overall health [73]. The consumption of fermented foods can enhance the diversity and functionality of gut microbiota. LAB, abundant in foods such as yogurt and kefir, play a crucial role in maintaining microbial balance in the gut, thereby supporting digestive health [74]. Additionally, LAB are known to alleviate symptoms of gastrointestinal disorders, including irritable bowel syndrome (IBS) and diarrhea, by normalizing intestinal function and reducing inflammation [75].

Lactic acid bacteria produce exopolysaccharides (EPS), which are metabolic compounds that play a crucial role in human health [76]. EPS isolated from fermented milk by *Lactobacillus helveticus* LZ-R-5 successfully identified R-5-EPS as a heteropolysaccharide with a molecular weight of approximately 5.41×10^5 Daltons. R-5-EPS exhibits potent immunostimulatory activity at the cellular level, as evidenced by increased proliferation of RAW264.7 macrophage cells, enhanced phagocytic activity, and elevated production of acid phosphatase, nitric oxide, and various cytokines [77]. These findings underscore the potential of R-5-EPS as a promising immunomodulatory agent. In addition to immunomodulatory activity, EPS demonstrates antiproliferative effects against various tumor cell types, including those derived from the intestine, liver, and breast. The mechanisms involved include the induction of apoptosis, cell cycle arrest, and antimutagenic, antioxidant, antiangiogenic, and anti-inflammatory properties [78]. At the genetic level, the structure of EPS synthesized by LAB is highly diverse, primarily influenced by glycosyltransferase genes that determine monosaccharide composition. EPS synthesis occurs via both extracellular pathways and Wzx/Wzy protein-dependent pathways [79].

Table 1. **The role of fungi in Indonesian fermented foods**
Таблица 1. **Роль грибов в индонезийских ферментированных продуктах**

Fungi	Indonesian fermented food	Role	References
S. cerevisiae	Tapai Singkong, Peuyeum, and Tape Ketan	convert sugars into alcohol and carbon dioxide; give a characteristic sweet and slightly alcoholic flavor	[64]
S. fibuligera and *W. anomalus*	Brem	hydrolyze starch into sugars; produce ethanol and amylase; provides a unique flavor	[65]
A. oryzae, A. sojae	Tauco (Taoetjo)	produce enzymes that break down proteins and carbohydrates, resulting in a unique flavor and texture	[66,67]
N. sitophila and *R. microsporus* var. *oligosporus*	Oncom	break down complex carbohydrates in the soybeans, making them more digestible and increasing their protein content	[68]
Aspergillus sp. and *Rhizopus* sp	Kecap manis	produce enzymes that break down proteins and carbohydrates, resulting in a unique flavor and texture	[69,70]

The diverse health benefits of EPS are evident from studies on various LAB strains. Among 48 strains screened for high EPS production, *Lactiplantibacillus plantarum* MY04 exhibited the highest yield (1.15 g/L) [79].

In addition to high EPS production, MY04 shows good resistance to harsh digestive conditions, strong antibacterial activity, and high intestinal adhesion capacity. Comprehensive genomic analysis confirms the safety of MY04 for human consumption, as it lacks virulence factors and antibiotic resistance genes, making it a promising probiotic candidate for the development of functional food products [80]. EPS produced by *Limosilactobacillus fermentum* NCDC400 (EPS400) has also been shown to significantly reduce cholesterol levels. In vitro, EPS400 removes more than 90% of cholesterol from the test medium and reduces cholesterol availability under digestive conditions. In vivo studies on hypercholesterolemic rats emphasizes that EPS400 administration can optimize lipid regulation by effectively lowering cholesterol. These findings demonstrate the potential of EPS400 as a candidate hypocholesterolemic agent in the food and pharmaceutical sectors [81]. Furthermore, EPS produced by LAB such as *Leuconostoc mesenteroides*, commonly found in fermented foods, acts as a prebiotic. This EPS is indigestible by the human body but serves as a substrate for beneficial gut bacteria. Fermentation of EPS by gut microbiota produces short-chain fatty acids (SCFAs), which function as bioactive molecules involved as metabolic regulators of glucose elevation and energy homeostasis stability. Consumption of EPS can also modulate gut microbial composition toward a more balanced state, thereby supporting overall health. Understanding the critical role of EPS produced by LAB provides new insights into the formulation of management and therapeutic strategies for diabetes and obesity, diseases frequently associated with lifestyle, through the optimization of functional foods [82]. Research on the role of commensal gut bacteria identifies *Streptococcus salivarius* as a unique bacterium with the potential to prevent obesity caused by excessive sucrose consumption. This bacterium produces high levels of EPS from sucrose, and its abundance is significantly lower in obese individuals. Additionally, the metabolism of EPS into SCFAs is impaired in obesity cases. These findings reveal an important mechanism in the interaction between the host and commensal bacteria via EPS-SCFA carbohydrate metabolism that affects energy regulation. They also suggest novel therapeutic potentials by targeting specific bacteria and EPS metabolites through prebiotics and probiotics for the prevention of lifestyle-related diseases [83].

LAB also contribute to strengthening the immune response by stimulating antibody production and modulating inflammatory pathways. These interactions help the body combat infections and potentially reduce the risk of autoimmune diseases [84]. Furthermore, the fermentation process carried out by LAB enhances the bioavailability of nutrients, facilitating the absorption of essential vitamins and minerals. Fermentation also produces beneficial compounds such as short-chain fatty acids (SCFAs), which contribute to metabolic health [85]. LAB in fermented foods interact intricately with the human immune system, offering various potential health benefits, including immunoregulation and disease prevention [86]. LAB and their fermented products play a role in regulating both innate and adaptive immune responses, potentially aiding in the management of inflammatory diseases [87]. In addition to maintaining gut microbiota balance, LAB contribute to optimizing digestion, nutrient absorption, and immune system function [88]. LAB modulate the functions of various immune cell types, including dendritic cells, macrophages, and regulatory T cells [89].

Beyond Lactic acid bacteria not only contribute positively to health, but the active metabolites produced during fermentation, such as antibacterial agents, lactic acid, and antifungal agents, can also improve food safety. In some fermentations, acetic acid is also produced, primarily by acetic acid bacteria (AAB), which alongside LAB contribute to inhibiting the growth of pathogenic microorganisms, preserving freshness, and extending the shelf life of food products [90]. However, like other food products, fermented foods face challenges related to safety. A deep understanding of the fermentation process and the microbial activity involved is essential to prevent health risks. Maintaining a balance of beneficial microorganisms during fermentation is key to ensuring product safety [75]. Suboptimal fermentation conditions, caused by poor hygiene practices or failure to control temperature, can hinder the dominance of beneficial microbes and lead to contamination by harmful bacteria, fungi, or toxins [91]. If fermentation practices are not properly controlled, there is a risk of pathogenic bacteria growth, such as *Salmonella spp.*, *Escherichia coli*, and *Listeria monocytogenes* [92]. Therefore, the implementation of Good Manufacturing Practices (GMP) and Hazard Analysis Critical Control Point (HACCP) principles is essential in the production of fermented foods.

From a nutritional perspective, fermentation by LAB, particularly from the *Lactobacillus* genus, can enhance nutrient availability through the production of enzymes such as amylase, protease, lipase, and glucoamylase. These enzymes act during fermentation to break down complex substrates, facilitating improved nutrient absorption. Additionally, *Lactobacillus* plays a role in breaking down phytic acid, an antinutritional compound that inhibits mineral absorption [73]. Fermented foods containing *Lactobacillus* and *Bifidobacterium* strains are known to contain various B-complex vitamins essential for body metabolism. LAB strains also exhibit metabolic activity that induces sensory changes in fermented foods, such as improved taste, aroma, and color, through the breakdown of organic compounds in the food matrix [93]. For example, the fermentation of cauliflower using *Lactobacillus plantarum* has been shown to increase protein content by 2.7%, from 10.4% to 13.1% after fermentation [94]. Additionally, the fermentation of temu giring rhizomes with *Lactobacillus bulgaricus* demonstrated an increase in phenolic and flavonoid compounds, as well as high antioxidant activity, with an IC50 value of 3.49 ppm [95]. Overall, the diversity and functional characteristics of lactic acid bacteria provide a spectrum of health benefits, making them relevant for use as a key component to improve community nutrition and disease prevention, as seen at Table 2.

Table 2. **The contribution and health benefits of lactic acid bacteria in Indonesian fermented foods**

Таблица 2. **Роль и польза для здоровья молочнокислых бактерий в индонезийских ферментированных продуктах**

Indonesian Fermented Food	Lactic Acid Bacteria	Contribution and Health Benefits	References
Tapai singkong	*Pediococcus acidilactici* and *Weissella cibaria*	*P. acidilactici* enhances protein and antioxidant content, while *W. cibaria* produces EPS. Both contribute to improved gut health	[96–99]
Peuyeum	*Weissella* sp., *Lactobacillus* sp. and *Lc. mesenteroides*	These bacteria have the biochemical pathways to produce various organic acids, including lactic acid, which contribute to the unique flavor and characteristics of peuyeum	[100]
Brem	*Lactobacillus* sp., *Leuconostoc* sp., *Pediococcus* sp., and *Weissella* sp.	Contribute to the distinct sweet and sour flavor of brem	[101]
Shrimp paste (terasi)	*Tetragenococcus, Halococcus, Atopostipes, Alkalibacillus,* and *Alkalibacterium*, along with *Lactiplantibacillus plantarum*	These bacteria can break down proteins and lipids, influencing the taste and aroma of shrimp paste by generating volatile compounds such as amino acids, aldehydes, organic acids, fatty acids, amines, and peptides	[100,102]
Tauco	*Lactobacillus* genus	Creates a low-pH environment.	[103]
Oncom	*Lacticaseibacillus paracasei* and *L. plantarum*	Produce organic and amino acids, contributing to the umami taste	[104]
Dadih	*Lactococcus* sp., *Klebsiella, Lactobacillaceae, Bifidobacterium, Streptococcus* sp., *Leuconostoc* sp., *Limosilactobacillus fermentum, L. pentosus, P. pentosaceus, Lactococcus lactis* subsp. cremoris, *L. lactis* subsp. lactis, *L. plantarum, L. casei*, and *L. rhamnosus*	Generates metabolites which inhibit pathogenic bacteria, thus contributing to dadih safety.	[41,42,105]
Kecap manis	*Hansenula* sp., *Zygosaccharomyces* sp., and *Lactobacillus* sp.	Produce protease enzymes that break down the proteins in soybeans into amino acids, resulting in the distinctive umami flavor of soy sauce.	[106]
Tape ketan	*L. mesenteroides, Liquorilactobacillus vini, W. paramesenteroides, P. pentosaceus, L. fermentum,* and *Apilactobacillus kunkeei*	Lactic acid bacteria contribute to the production of lactic acid through anaerobic glucose fermentation, which gives tape its characteristic sour taste	[107,108]
Acar pickles	*L. plantarum, L. mesenteroides*, and *L. citreum*,	These bacteria can reduce the number of biogenic amines (BA) during fermentation. The total count of mesophilic aerobic bacteria and yeast-mold colonies in pickle samples containing *L. plantarum* appeared to be significantly reduced	[109,110]

Overall, the consumption of Indonesian fermented food can contribute to improved gut health, potentially supporting overall well-being and providing a range of health benefits. Integrating a variety of naturally fermented foods into a balanced diet may promote a healthy gut microbiota and enhance overall health.

6. Nutritional facts

Fermented foods are often rich in a variety of nutrients, depending on the ingredients used and the specific fermentation process. The nutritional composition of fermented foods can vary based on several factors, including the fermentation method, the raw materials, the duration of fermentation, and the specific types of microorganisms involved [59]. Additionally, fermentation frequently enhances the nutritional value of raw ingredients. The microorganisms involved produce enzymes that break down complex compounds into simpler, more easily digestible forms [111]. For instance, fermentation can increase the concentrations of certain vitamins, such as B vitamins, and improve the bioavailability of minerals. It can also reduce the levels of antinutritional factors naturally present in some foods, such as phytates in grains and legumes, thereby enhancing the absorption of essential nutrients [112]. Furthermore, the final nutritional profile of fermented foods is strongly influenced by the type of raw material used. Vegetable fermentation typically yields products rich in vitamins and antioxidants, whereas dairy fermentation results in foods with high protein content [113,114]. The combination of different raw materials and variations in fermentation techniques produces a diverse range of products, each with unique nutritional characteristics, contributing to the wide array of potential health benefits associated with fermented food consumption. Common nutrients found in fermented foods are summarized in Table 3.

7. The influence of fermentation on food shelf life

Fermentation is a food preservation method that plays a significant role in enhancing nutritional quality, extending shelf life, and influencing food functionality. This process can enhance the flavor and aroma of fermented products [121]. However, the shelf life of fermented products varies greatly, depending on the product type, packaging method, and fermentation conditions. For example, some products have a relatively short shelf life of 2 to 4 days, influenced by the type of packaging and fermentation conditions. Packaging with banana leaves can extend the shelf life up to 4 days, while fermented foods in plastic packaging only lasts about 2–3 days [122]

Differences in shelf life were also observed in shrimp paste (terasi). Commercial shrimp paste generally exhibits a longer shelf life (6–12 months in sealed packaging and 1–3 months after opening in refrigeration) compared to homemade shrimp paste (1–2 weeks in refrigeration). Optimal storage and packaging conditions are crucial to extend the shelf life of both types of shrimp paste [123]. Other fermented products, such as tauco, also undergo changes during storage. Although initial micro-

Table 3. **Nutritional information for fermented foods per 100 g**

Таблица 3. **Информация о пищевой ценности ферментированных пищевых продуктов на 100 г**

Fermented foods	Nutrients	Number	References
Tapai Singkong	Energy (Kcal)	169	[115]
	Carbohydrate (g)	40.20	
	Protein (g)	1.40	
	Fat (g)	0.30	
	Calcium (mg)	21	
	Phosphorous (mg)	34	
	Iron (mg)	0.80	
	Vitamin C (mg)	9	
Brem	Energy (Kcal)	249	[116]
	Carbohydrate (g)	58	
	Protein (g)	3.40	
	Fat (g)	0.40	
	Calcium (mg)	198	
	Phosphorous (mg)	86	
	Iron (mg)	2	
	Total carotene (µg)	240	
	Thiamine (mg)	0.34	
Terasi	Protein (%)	64.80	[115]
	Fat (%)	3.45	
	Ash (%)	1.40	
	Water (%)	25.77	
Solid tauco	Carbohydrate (g)	54.7–65.2	[117]
	Protein (g)	9.72–11	
	Fat (%)	6.98–23.4	
	Ash (%)	10.0–22.8	
	NaCl (%)	7.18–16.9	
	Total sugars (%)	11.9–27.0	
	Total acids (%)	1.24–2.18	
	Total amino acids (%)	11.4–17.5	
Liquid tauco	Carbohydrate (g)	8.47–56.5	[117]
	Protein (g)	20.4–30.9	
	Fat (%)	1.30–18.9	
	Ash (%)	17.1–73.89	
	NaCl (%)	10.7–68.4	
	Total sugars (%)	29.95–44.5	
	Total acids (%)	1.65–5.36	
	Total amino acids (%)	14.1–24.6	
	GABA (ppm)	220.96	
Red oncom (oncom merah)	Energy (Kcal)	97.70	[118]
	Carbohydrate (g)	55.59	
	Protein (g)	24.16	
	Fat (%)	16.10	
	Total sugar (%)	0.80	
	Total titratable acidity (%)	0.15	
	Total soluble protein (%)	39.94	
	pH	4.87	
	Moisture (%)	80.56	
	Ash (%)	4.14	
	GABA (ppm)	136.92	
Black oncom (oncom hitam)	Carbohydrate (g)	16.55	[118]
	Protein (g)	40.60	
	Fat (%)	40.47	
	Total sugar (%)	0.17	
	Total titratable acidity (%)	0.10	
	Total soluble protein (%)	32.97	
	pH	5.8	
	Moisture (%)	52.98	
	Ash (%)	2.38	
Dadih	Water (%)	82.10	[43]
	Protein (%)	6.99	
	Fat (%)	8.08	
	Lactose (%)	5.29	
	Vitamin A (IU/g)	70	
Kecap manis	Carbohydrate (g)	28.40	[119]
	Protein (g)	18.20	
	Lipid (g)	3.20	
	Ash (g)	1.50	
	Glucose (g)	0.39	
	Lactic acid (g)	1.92	
	Salt content (g)	17.04	
	Moisture (g)	48.70	
Tape ketan	Energy (Kcal)	166	[120]
	Carbohydrate (g)	34.4	
	Protein (g)	3.8	
	Fat (%)	1.0	
	Fiber (g)	0.60	
	Ash (g)	0.10	
	Calcium (mg)	8	
	Phosphorus (mg)	106	
	Iron (mg)	1.6	
	Thiamine (mg)	0.40	

biological analysis indicated that the tauco met food safety requirements, storage at room temperature for 12 days resulted in an increase in total microbial counts, molds, yeasts, and coliforms above permissible limits. However, the pH value of the tauco chili sauce tended to remain stable throughout the testing period [124]. The shelf life of kecap manis using Accelerated Shelf-Life Testing, revealing a shelf life of 127.92 days or 4.26 months at a temperature of 25 °C [125]. Meanwhile, sterilized black glutinous rice tape exhibits a shelf life influenced by storage temperature. Higher storage temperatures correlate with shorter shelf lives. At room temperature (25 °C), sterilized black glutinous rice tape can last approximately 1 year and 9 months [125]. Oncom, another fermented product, has a very short shelf life of about 1–2 days at room temperature [126]. This indicates that oncom is highly susceptible to spoilage due to physical, chemical, enzymatic, or microbiological changes. Consequently, the shelf life of fermented products varies widely, depending on product type, packaging methods, and fermentation conditions. Some products, such as cassava tape and oncom, have very short shelf lives, while others, like commercial shrimp paste and sterilized black glutinous rice tape, can last longer. Therefore, it is crucial to understand the factors affecting the shelf life of fermented products to implement proper storage and packaging practices that extend shelf life and maintain product quality.

8. Technological advancements to improve fermented food: Challenges and future prospects

Technological advancement aims to optimize fermentation processes, improve product consistency, diversify product offerings, enhance nutritional qualities and meet consumer demands for high-quality, innovative fermented food option. The following are some ways to improve product quality.

8.1. Strain selection and genetic engineering

The growth of the global population and the impacts of global warming necessitate an

increase in food production, storage, and transportation [127]. Modern biotechnology, including strain selection and genetic engineering, holds significant potential for expanding the scope of fermentation, creating novel foods, and enhancing the sustainability of food production [128]. Food fermentation has been practiced since antiquity, initially relying on indigenous microbiota and spontaneous fermentation, which later evolved into back-slopping and the utilization of starter cultures [129]. Specific strains of beneficial microorganisms, such as lactic acid bacteria and yeast, in fermented food can improve desirable flavors and textures, affecting sensory characteristics, extend shelf-life, prevent spoilage bacteria, and present health benefits [130,131]. With technological advancements, genetic engineering has reached a high level of precision, enabling modifications to virtually any aspect of the genome. Synthetic biology also offers new opportunities in addressing food production challenges [132].

Genetic modification techniques in beneficial microorganisms are being explored to enhance certain microbial strains used in fermentation. Strain improvement is typically reached by random mutagenesis, process optimization, control, increasing the yield, titer and cost-effectiveness [133]. This can potentially improve fermentation efficiency, resistance to environmental stressors, and production of specific compounds that contribute to the quality or nutritional value of the final product. Additionally, Indonesia has established regulations governing the hygiene and safety of genetic engineering product, as outlined in the Government Regulation of the Republic of Indonesia Number 21 of the Year 2005 and Regulation of the Badan Pengawas Obat dan Makanan (BPOM) Number 6 of the Year 2018. These regulations pertain to the control of genetically modified food products [134,135].

Additionally, there are constraints in applying genetic modifications to food systems [136]. Further challenges arise in handling non-model microorganisms, including the development of suitable molecular genetic tools [137]. Beyond the potential benefits, there are risks associated with the use of genetically modified microorganisms in food fermentation. The consumption of genetically engineered foods may lead to the development of antibiotic-resistant diseases. Another risk is the potential transfer of antibiotic and chemotherapy resistance genes into the body through fermentation products, potentially leading to multidrug-resistant strains that are difficult to treat [75]. Modern biotechnology offers significant opportunities to enhance food production and sustainability through fermentation. However, challenges such as technical constraints in handling non-model microorganisms and risks associated with genetically modified microorganisms need to be addressed to ensure the safety and sustainability of application of these technologies in food production. The Indonesian culture context, which is not yet familiar with genetically modified microorganisms, will pose a new challenge for Indonesia in the future.

8.2. Fermentation control systems and bioreactors

Advanced fermentation equipment and techniques allow for precise control of temperature, humidity, pH levels, and oxygen exposure during fermentation [138]. This control ensures the optimal condition for microbial growth and metabolic activities, assessing the progress of fermentation, resulting in more predictable, consistent, and higher-quality fermented products. Bioreactors provide controlled environments for fermentation on a larger scale. These systems help maintain optimal condition, leading to efficient and standardized production of fermented foods. Several factors affecting the bioreactor involve temperature and pH control, agitation and aeration, nutrient concentration, air pressure, contamination, size and design of bioreactor [139].

At an industrial scale, maintaining consistent heat and humidity levels presents a significant challenge due to the large volume of substrate involved. In solid-state fermentation (SSF), which relies on filamentous fungi, the delicate hyphae are highly susceptible to damage from mechanical agitation, posing a major constraint [140]. Therefore, maintaining optimal process conditions is crucial to achieving the desired yield and titer, regardless of the bioreactor configuration, the biocatalysts used, or potential process disruptions [141]. Ongoing research and innovation in biorefinery technology and product diversification play a vital role in unlocking the full potential of fermentation by-products. These advancements are also key to realizing the vision of a sustainable and circular bioeconomy [142]. One of the latest innovations in this field is the development of single-use bioreactors. These bioreactors are made from high-quality plastic materials such as low-density polyethylene, polypropylene, or polycarbonate. The use of single-use bioreactors eliminates the need for cleaning and sterilization between cultivation batches, reducing the risk of contamination while also simplifying validation processes and regulatory compliance [143]. Challenges in fermentation and bioreactor control include the difficulty of maintaining optimal conditions at an industrial scale and the vulnerability of fungal hyphae in SSF. Innovations such as single-use bioreactors provide solutions to minimize contamination risks and streamline processes. Further research and development in biorefinery technology and product diversification are essential to maximizing the potential of fermentation in achieving a sustainable bioeconomy.

8.3. Omics technologies

Harnessing synthetic biology for designing microorganisms with customized functions and traits enables the creation of novel fermented products. Genomics, transcriptomics, proteomics and metabolomics provide a comprehensive understanding of the microbial communities involved in fermentation processes. These technologies enable the identification and optimization of key microorganisms, genes, and metabolic pathway. The complexity of biological systems presents significant challenges in the application of omics technologies to fermented fruits and vegetables [144]. The vast amount of data generated by multi-omics technologies requires robust bioinformatics infrastructure and expertise [145]. Additionally, understanding the intricate and dynamic changes within microbial communities during spontaneous fermentation remains a major challenge [146]. The lack of comprehensive omics data repositories and universal databases further affects the accuracy of predictive models [144]. Nevertheless, the multi-omics approach provides in-depth insights into the dynamic microbial shifts occurring throughout food fermentation, surpassing single-cell omics analyses. This approach enables the exploration of the entire microbial community involved and facilitates the regulation of microbiota changes at each fermentation stage [145]. Omics technologies also play a crucial role in optimizing fermentation processes and improving product quality. For instance, multi-omics tools can be employed to evaluate the impact of various ingredients on fermentation dynamics and the resulting end products [129]. Despite the challenges associated with biological system complexity and the need for advanced bioinformatics infrastructure, multi-omics approaches hold great potential for understanding and optimizing food fermentation processes. These technologies offer profound insights into microbial changes and the key factors influencing the quality of fermented products. Therefore, continued research and development in this field are expected to enhance fermentation efficiency and improve the quality of fermented food products.

8.4. Improved packaging and storage

Innovations in packaging materials and techniques help maintain the quality and extend the shelf life of fermented foods by protecting them from oxygen, light, moisture, and microbial contamination. The storage duration and temperature can impact the bacterial survival. Therefore, enhancing packaging and storage conditions, considering environmental temperature, light exposure, oxygen levels, is crucial to significantly reduce the loss of viable bacteria [147].

Food safety threats and microbial spoilage risks are persistent challenges faced by the food industry. Storage duration and temperature significantly influence bacterial survival [148]. Environmental temperature manipulation can help mitigate the loss of viable bacteria. Another key strategy for enhancing microbial viability in food involves minimizing oxygen exposure through packaging modifications, incorporating antioxidant compounds, or controlling environmental light exposure [149]. Higher temperatures (37 °C) lead to the most significant reduction in microbial populations, while lower temperatures (−20 °C and 4 °C) are more effective in preserving microbial viability. Vacuum packaging primarily affects moisture retention, with vacuum-sealed packaging being superior in maintaining product moisture content. The optimal storage conditions for fermented products involve non-vacuum packaging and storage at freezing or refrigeration temperatures for no longer than three months [147]. The life cycle of fermented food packaging comprises several key phases, each with unique environmental considerations, including raw material extraction, manufacturing, distribution, consumer use, and end-of-life management, which encompasses byproducts and waste disposal. Sustainable practices, such as utilizing recyclable or compostable materials, optimizing packaging design, and minimizing energy consumption during manufacturing, are essential to reducing environmental impact and aligning with consumer preferences for eco-friendly options [150].

Maintaining optimal humidity levels is crucial for the quality and safety of fermented dairy products. Active packaging systems regulate humidity by either absorbing excess moisture or releasing it as needed. This humidity control helps prevent product deterioration, such as clumping caused by moisture or the growth of undesirable microorganisms [151]. Antimicrobial coatings integrated into the packaging materials provide an additional layer of protection against harmful microbes. Naturally derived antimicrobial compounds, such as those extracted from edible plant sources like anise, have been evaluated for their technical and economic feasibility in industrial-scale applications [152,153]. These coatings gradually release antimicrobial agents, inhibiting the growth of spoilage bacteria and pathogens that may compromise product quality and safety. This technology not only extends shelf life but also enhances the overall safety and quality of the product.

8.5. Fermentation in novel substrates

The substrate type, fermentation time and sugar type were the primary factors contributing to the significant increase in the content of bioactive compounds, which exhibit beneficial antioxidant properties. Researchers are exploring the use of alternative raw materials or substrates for fermentation to create new types of fermented foods. This includes exploring fermentation in plant-based products, grains, and unconventional sources to cater to diverse dietary preferences and meet specific nutritional needs [154].

Emerging fermentation techniques have attracted significant attention from researchers and the food industry due to their potential to integrate traditional foods into modern diets and to enable the fermentation of unconventional substrates and food by-products. Inoculation of *Lacticaseibacillus rhamnosus* on date palm substrate facilitates increased bioavailability of phenolic compounds [155]. The combination of non-traditional substrates with specific microbial strains can result in novel fermented foods with enhanced nutritional profiles and improved organoleptic properties [127]. The development of these new fermented products aims to promote better nutrition, sustainability, and health benefits [156]. Innovations in this field include the utilization of agricultural by-products, biomass fermentation for protein production, the use of fruit seeds such as rambutan seeds, non-dairy substrates, and various plant parts such as roots and tubers [157].

8.6. Scale-up of traditional process

The enlargement of microbial processes is usually carried out with a commercial objective, particularly to deliver product advantages to consumers and to generate a financial profit for investors. Technologies and strategies for scaling up small-batch artisanal fermentation to larger production levels are being developed. Indonesian fermented foods are still predominantly produced by Micro, Small, and Medium Enterprises. This allows traditional fermented foods to be produced on a commercial scale while maintaining their unique characteristics. However, translating laboratory-scale advancements to large-scale production can pose challenges, including maintaining consistent condition and dealing with increased complexities [158].

Traditional fermented foods are significant sources of protein, vitamins, minerals, and other essential nutrients [159]. However, the limited application of modern biotechnology has hindered clinical exploration of their gut-modulating health functions [160]. Among the most under-explored categories of traditional foods are those originating from African and Asian countries, despite published data indicating their high nutritional value [161]. The modernization and commercialization of these products will ultimately determine their success as mainstream commodities in global markets. Key priorities will include ensuring safety, meeting hygiene standards, and preserving product-specific characteristics [162,163]. To commercialize traditional fermentation processes, industry stakeholders must address challenges related to safety and product consistency. Additional barriers include ethical and regulatory considerations, difficulties in applying research findings due to the high costs of effective methodologies, the expense of analyzing and interpreting high-dimensional data, and the issue of low reproducibility [164,165]. To bring precision-fermented products to market, companies must also navigate a complex and diverse regulatory landscape, including frameworks established by the FDA and EFSA in the United States and Europe, as well as national standards such as Indonesia's SNI [166,167].

9. Conclusion

This review elucidates the pivotal role of fermentation in preserving Indonesia's culinary heritage through traditional foods like tempeh, peuyeum, and kecap manis. Examining their origins, production methods, and the involvement of microorganisms, especially lactic acid bacteria, highlights their unique flavors and considerable nutritional benefits. The diverse production processes, raw material choices, and regional influences contribute to the distinct tastes in these fermented foods, enriching Indonesia's culinary landscape and revealing cultural nuances. Amid globalization, safeguarding these traditional fermentation methods is crucial to maintain culinary authenticity and cultural heritage. Preserving these practices not only protects them from extinction but also sustains cultural identity, fulfills nutritional needs, bolsters local economies, and promotes indigenous food resources for economic growth. Therefore, this study emphasizes the importance of cherishing Indonesia's diverse fermented foods. This not only preserves culinary traditions but also fosters cultural sustainability, celebrates culinary diversity, and supports overall well-being in the food industry's broader context.

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