Journal of Ethnic Foods

REVIEW ARTICLE

Open Access

Exploring tempoyak, fermented durian paste, a traditional Indonesian indigenous fermented food: typical of Malay tribe

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Abstract

Tempoyak is a traditional Indonesian fermented durian paste that is popular among the Malay ethnic community. While tempoyak is a distinctive, culturally significant culinary item in multifarious Indonesian cuisine, it remains understudied compared to other fermented foods like kimchi. Further research is called for to understand tempoyak's microbial structure, dynamics, and potential health advantages that include immunostimulants, antihypercholesterolemia, probiotic action, preservatives, and antibacterial. Researchers can also reveal significant information on the history, ethnicity, production, microbiological challenges, nutritional and functional qualities, and future possibilities of indigenous food, including tempoyak. This research aimed to explore and investigate tempoyak as an indigenous fermented food by integrating a systematic literary research and data from earlier investigations. Tempoyak is closely associated with Malay identity, regardless of the place they dwell. As an essential part of everyday life in Malay community in Indonesia, tempoyak is commonly served at traditional ceremonies, wedding festivities, or large-scale events. This cultural importance makes Indonesian tempoyak distinct from its Malaysian counterpart. Tempoyak is made by crushing durian flesh, adding salt into it, and letting the homogeneous mixture sit at room temperature in a covered container for 4–7 days. The microfloras present in tempoyak are varied but primarily *Lactobacillus* sp., notably *Lactobacillus plantarum*. Proximate analysis is a viable method to assess the nutritional composition of tempoyak. Variations in nutritional content may occur due to differences in durian types, salt composition, sterilization time, temperature, and fermentation duration. Potential avenues for further studies include the role of tempoyak in fostering sustainable food systems, other health advantages of ingesting tempoyak, and the creation of novel tempoyak-based products. These study directions will further enhance the discipline and contribute to the preservation and promotion of Malay culinary heritage.

Keywords Fermentation technology, Functional food, Indonesia, Malay tribe, Tempoyak, Traditional fermented food

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Introduction

Ethnic Food is an essential element of culture and history. It reflects the customs, values, and beliefs of a society [1, 2], and is an essential aspect of social gatherings and celebrations [3], historical changes, and cultural identity [4–6] represented in distinctive culinary routines, recipes, and preparation techniques. Documenting these meals helps conserve and enhance cultural history for the future generations and attract people to experience unique culinary traditions, thus generating greater incomes and prospective employment for local communities [7]. Kimchi, for example, is an ethnic cuisine that has been thoroughly recorded in 974 articles investigating different aspects, including its features, quality, sensory evaluation, microorganisms for fermentation, and health benefits such as immune-enhancing properties, antidiabetic, chemopreventive agents, and antioxidant agents [8].

Despite fitting in the same category of fermented food, tempoyak is still less popular than kimchi. While kimchi is made of cabbage or raddish, tempoyak is fermented durian paste produced from overripe durians, either with or without salt [9–11]. According to Rahman in Haruminori [12], "tempoyak" is derived from the word "poyak" which means "torn". Therefore, tempoyak refers to the cooking method, that is breaking durian into pieces [13].

The fermentation process of tempoyak is spontaneous, relying on the indigenous microbes present in the durian, particularly lactic acid bacteria (LAB) [9, 10]. Durian is placed in a sterile, closed container and fermented at a temperature (28–34 °C) for 4–7 days [14]. The nutritional contents of tempoyak includes carbohydrates, protein, fat, ash, moisture content, and a pH level of 3.69 [14]. Tempoyak has been reported to have various nutritional, functional, and probiotic properties such as acid and bile salt tolerance, antioxidative and anti-proliferative activities, and exceptional adhesion to the Ht-29 colon cancer cell line [15]. Also, consumption of tempoyak has evidently reduced cholesterol [16, 17].

Despite the fact that kimchi and tempoyak have been the subject of several studies, significant research gaps remain. Tempoyak, a lesser-known fermented cuisine, is understudied compared to kimchi in terms of microbial structure and dynamics of tempoyak fermentation and possible health benefits. In the field of food science and technology, further research need to focus of tempoyak flavor, texture, bioactive components, and nutritional contents that vary depending on the types of durian, fermentation procedure, and the storage conditions in order to contribute to the greater field of food science and technology. To obtain more robust data, studies on tempoyak should integrate the existing materials, identify research gaps, and provide a comprehensive understanding of this distinctive fermented product. This may help preserve tempoyak as a cultural heritage, promote its potential health benefits, and research its applications in food and health industries.

This research aims to give a full assessment of the history and culture of tempoyak fermentation as well as the production method, nutritional value, microbiological characteristics, taste, and texture. Understanding the microbial structure, fermentation process, and sensory characteristics of tempoyak may help researchers and community in tempoyak preservation, quality control, potential food industry uses, and anticipation of tempoyak production in the future.

Methods of review

This literature review identified, analyzed, and synthesized essential information from many sources including books, journal articles, and other published materials. The materials were summarized as an overview of the present state of knowledge on tempoyak, highlighting the gaps in the existing research and suggesting topics for future research. This literature review focused on the existing research on microorganisms proliferated in fermented durian, their participation in the fermenting process, the nutrient content of tempoyak and durian, the history and manufacture of tempoyak, their potential health advantages, and the challenges and opportunities of tempoyak.

The sources were collected from databases and search engines for academic research, namely Google Scholar, ScienceDirect, Scopus, and JSTOR. The inclusion criteria were studies published in peer-reviewed journals/proceeding/books, studies that focus on the microbial aspects, flavor, and texture of tempoyak fermentation and durian, studies that provide information on the traditional preparation methods and cultural significance of tempoyak, fruit and vegetables fermentation, and studies that include sensory analysis, and nutritional composition. The exclusion criteria were studies not available in English and Indonesian language. The keywords for database searches were tempoyak, fruit fermentation, vegetable fermentation, fermentation process, LAB fermentation, LAB and tempoyak, proximate content, bioactive compounds, probiotics, food and culture, and the history of tempoyak. The year of publication was limited to 1969–2023. All relevant academic papers collected from the searches utilized mixed methods of qualitative and quantitative data for analysis.

History and culture of tempoyak

Tempoyak has a distinctive name and appearance (see Fig. 1). Numerous Malayan ethnics living in areas of Indonesia, notably Lampung, Jambi, South Sumatra,

Fig. 1 Durian in a plastic container and will be fermented (Left) and Tempoyak after fermented (Right) [18] *Source*: Yuliana

West Sumatra, and Kalimantan, are familiar with this fermented durians by different names like sour durian, pickled durian, and tempoyak [18]. Figure 2 illustrates the prevalent areas producing traditional tempoyak in Sumatra and Kalimantan, but more concentrated in South Sumatra and West Borneo. According to Rahman in Haruminori [12], the term tempoyak is derived from how the food is made because the word "poyak" means "torn," so tempoyak refers to torn apart durians.

Tempoyak is a daily food item in Malay culture, reflecting a strong cultural identity. Tempoyak-based dishes are served at delis and restaurants in Sumatra, for guests in a home, or in traditional rites such as "tahlilan" (vigils or wakes), "sholawatan" (Islamic prayer gathering), wedding festivities, or large-scale festivals. As part of ethnocultural identity, tempoyak is strongly suspected to have spread to various regions as the Malays people migrate to various regions and formed states, which is today's Indonesia, Malaysia, and Brunei [19]. People relocating or migrating to a different region generally have the desire to reconnect with their past and cultural roots that have been ingrained and passed on from one generation to another [20–22].

Malay ethnic group includes the country Malaysia (West Malaysia and adjacent East Malaysia) Southeast Asian islands, such as Sumatra, Kalimantan/Borneo, and other smaller islands [12]. Malay ethnicity refers to Borneo people who have established or evolved in Sumatra and Malaysia as a consequence of their subsistence culture, which involves trading and sailing [19, 20]. As a consequence of this dispersal, their civilizations grow and transfer across geographical borders, assimilating Malay ethnicity and other tribes along the way.

Regardless of different geographical locations that generate distinctive ethnic characteristics and implications on ways of living and beliefs [23], tempoyak has always been connected with Malay identity [5, 6]. Tempoyak knowledge is passed down through marriage or migration, constructed and carried out with existing natural resources and preferences in mind.

Out-migration, or "merantau" in Bahasa Indonesia, is a way of life of indigenous Sumatran tribe. Being nomadic

Fig. 2 A geographical map of the origin of tempoyak fermented cuisine in the Indonesian region (South Sumatra: orange color, West Borneo: yellow color)

people, Sumatrans are used to preparing food for their journey, so they rely heavily on preserved foods like tempoyak [12]. A Malayan-native renown litterateur, Abdullah bin Abdulkadir Munsyi, narrated in his book "Hikayat Abdullah" that when visiting Terengganu in 1836, he stumbled across Tempoyak, a meal that smelled bad but popular among the Malay ethnic community. According to his trip notes, the Malay community appreciated tempoyak and regarded it as an appetite stimulant [12].

While tempoyak is popular in Indonesian and Malaysia, it has some notable differences (see Table 1). Indonesian tempoyak is versatile—a sauce on its own or an additional ingredient in processed fish, owing to its sour and salty taste. Malaysian tempoyak, on the other hand, is a typical condiment or a key ingredient in meals like tempoyak curry or tempoyak fried rice. This contrast in culinary applications demonstrates unique ways in which culture is embedded in tempoyak-based cuisines. Meanwhile, tempoyak is a traditional durian-fermented condiment that goes with fish or vegetable meals in Singapore, Brunei, and potentially Southeast Asia as a whole [27, 28].

Other contributing factors to these differences are varied durian cultivars, fermentation techniques, and culinary traditions [29]. Food is among other cultural manifestations of a civilization that differs from place to place since it is tied to natural resources, beliefs, ethnicity, technology, and contact with other cultures [21, 22]. These attributes distinguish variety of food despite sharing a common name [30–32].

Production of tempoyak

Food processing is associated with food preservation that gives it a particular flavour. Fermentation is a processing method that has been employed since ancient times [24, 33], and common in the majority of Indonesian traditional cuisines to produce regional specialties. When implanted in a sterile and covered container at room temperature (28–34 °C) for 4–7 days, durian can undergo a spontaneous fermentation and turn into tempoyak [14]. Tempoyak can be processed physically, chemically, or microbiologically (with yeast, fungus, or LAB) where durian is turned into a semi-solid substance with a strong acidic aroma [18]. Making tempoyak is historically equal to kimchi production in Korea that used clay pots but has now used other containers, such as jars. Fermentation container is claimed to influence unusual acidic flavour of fermented products [34].

Figure 3 displays the natural fermentation of tempoyak in many areas of Indonesia. The quantity of salt used in making tempoyak impacts the texture, smell, and total LAB [35]. The quantity of salt used to produce tempoyak in the community varies widely (2.5–30% w/w), but the most preferred is 3% w/w in Indonesia [35] and 2% NaCl in Malaysia [36]. The common temperature for fermenting tempoyak is 28–34 °C in Indonesia and 28 °C in Malaysia [14, 36].

The added salt can produce two varieties of tempoyak, < 5% salt produces acidic tempoyak and > 5% salt produces salted tempoyak [18, 37]. Fermentation that uses minimum salt content is supportive for LAB growth to produce highly acidic food in a short time, while tempoyak is made with a lot of salt [18, 37] and lasts longer than that with a little salt [18]. Less salted tempoyak has a milder texture and more sour flavour, thus higher in total LAB [35]. The best temperature for optimum tempoyak fermentation is 27 °C and best consumed between the fourth and sixth days when the pH and sugar content have stabilized [38]. Tempoyak is of good quality when lactic acid levels are still elevated. The increase in lactic acid concentration takes place after being stored for 5–7 days. After 7 days, other organic acids, such as propionic acid and acetic acid, will increase in concentration [38].

Table 1 Consumption of tempoyak in distinct places in Indonesia and Malaysia

Regional origin	Tempoyak consumption	References
South sumatra	Tempoyak as a side dish with rice and spices. Brengkes, a classic South Sumatran dish, is a steamed fish wrapped in banana leaf and seasoned with tempoyak and spices rich in sour, sweet, savory, and spicy flavor	[12]
South aceh	Tempoyak goes perfectly with Indonesian curry or *gulai* in South Aceh, cooked in chili sauce with a little shrimp paste	[24]
Lampung	*Sambal seruit combo* is a grilled or fried fish mixed with shrimp paste	[25]
Jambi	Tempoyak is a prominent ingredient in meals like *gulai tempoyak ikan patin* (spicy curry catfish with fermented durian) and *gulai tempoyak* (spicy curry with fermented durian)	[24]
Bengkulu	Tempoyak is prepared as tempoyak snapper head curry and tempoyak sambal	
Pontianak, Kalimantan	Sambal tempoyak is served with shrimp, anchovies, and petai or bitter bean (*Parkia speciosa*)	[9]
Malaysia	In Malaysia, tempoyak is frequently served with boiling yellow fish stew or curry fish tempoyak and other meals like tempoyak with *Cassava* leaves and bitter bean	[9, 26]

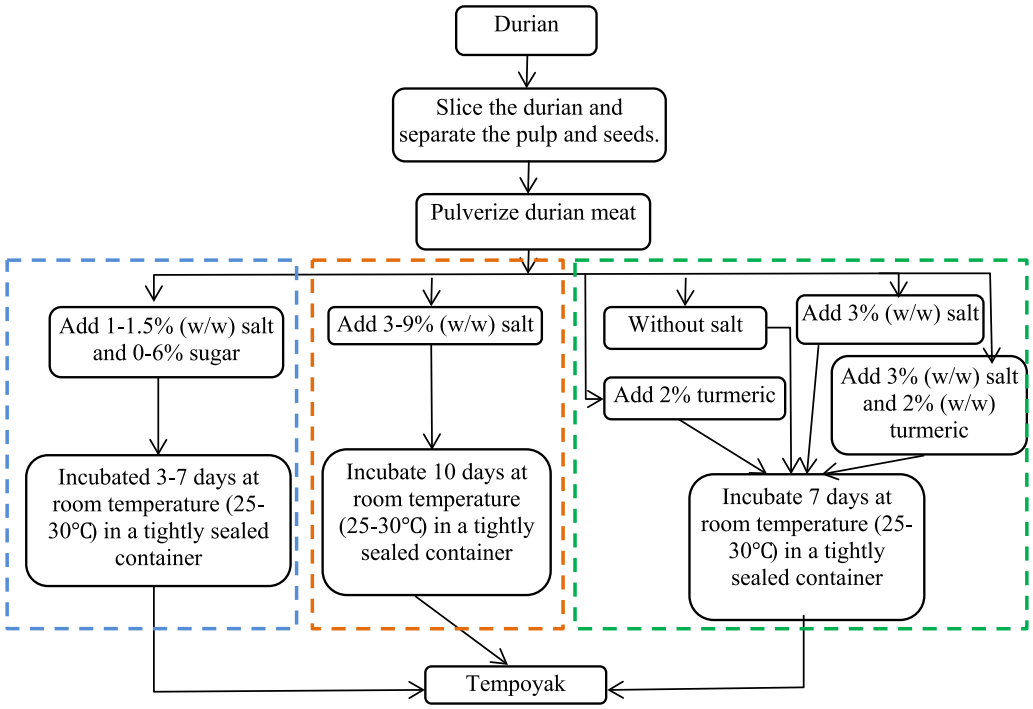

Fig. 3 Natural fermentation scheme of Tempoyak in several locations in Indonesia (blue dashed lines: Katapang, Kalimantan, orange dashed lines: Pontianak, Kalimantan, green dashed lines: Banda Aceh)

Spontaneous fermentation can grow unwanted microbes, such as pathogenic microbes that are toxic and contributing less desirable taste [18], and produce unstable and ununiform product quality. Modern tempoyak can use purified inoculum for better fermentation process and more manageable natural microbiota [39]. The use of appropriate starter cultures potentially improve microbiological control, hence enhancing lactic acid yield [40]. Yuliana [39] discovered that inoculums (*Pediococcus acidiliactici*) can enhance the microbiological features of tempoyak because total LAB in tempoyak require higher inoculum, and impurities or undesirable microorganisms can be kept at bay.

Microbial aspect in tempoyak fermentation

As a fermented product, tempoyak requires active microorganisms. Past investigations illustrated in Table 2 have revealed that LAB are the predominant microorganisms in tempoyak production. According to Chuah et al. [41], LAB involvement in the fermentation would increase the organoleptic qualities of tempoyak.

Bacteria present in tempoyak fermentation process may vary depending on factors such as durian variety, fermentation conditions, and indigenous microorganisms in the environment [9]. Chuah et al. [41] who identified the progressive succession of native LAB microorganisms in tempoyak natural fermentation reported that heterofermentative *L. mesenteroides* and *Fructobacillus durionis* were prominent in the early phases of fermentation while *F. durionis* remain dominant throughout the fermentation. Meanwhile, Ajibola et al. [36] found that the predominant LAB strains in tempoyak are *Weissella paramesenteroides*, *Enterococcus faecalis*, *Enterococcus gallinarum*, *L. plantarum*, *L. brevis*, *L. fermentum*, *L. mali*, *L. mesenteroides*, *L. casei*, and *Pediococcus acidilactici*.

The prevalent LAB in tempoyak fermentation are comparable to those in fermented vegetables such as sauerkraut [46–48] and kimchi [49–51]. *L. mesenteroides* are also detected in the early phases of vegetable fermentation where they generate considerable amounts of acetic acid, lactic acid, and carbon dioxide [46]. These fermented compounds will cause the pH to decrease and anaerobic conditions to develop. The resulting conditions stimulate the formation of homofermentative *Lactobacilli* that are more acid-resistant, such as *L. plantarum* [46].

The microbial fermentation process plays a vital role in the flavor and texture development of tempoyak [41]. The final product is influenced by the breakdown of intricate compounds, the generation of organic acids and enzymes, and microbial activity [52]. The presence of LAB can impact the flavor of processed foods in different ways. The metabolic process that ensues causes the

Table 2 Bacterial isolates reported from investigations on tempoyak of different provenance

Tempoyak origin	Bacteria species	References
Bengkulu (Indonesia)	*Pediococcus acidilactisi*, *Lactobacillus plantarum*, *Lactobacillus curvatus*, *Leuconostoc mesentroides*, *Staphylococcus saprophyticus*, *Micrococcus* varians	Hasanuddin [42]
Parung Bogor (Indonesia)	*Lactobacillus plantarum*, *Lactobacillus Casei*, *Lactobacillus fermentum*	Reli et al. [43]
Pekanbaru, Riau Province, (Indonesia)	*Enterococcus sp.* *Enterococcus gallinarum* *Enterococcus faecalis* *Lactobacillus sp.*	Pato and Surono [16]
Kalimantan (Indonesia)	*Streptococcus*, *Lactobacillus*	Permatasari et al. [35]
Kuala Terengganu and Marang (Malaysia)	*Lactobacillus buchneri*, *Lactobacillus plantarum*, *Lactobacillus brevis* I *Lactobacillus acidophilus* I *Lactobacillus paracasei*, *Lactobacillus buchneri*, *Lactobacillus parabuchneri*, *Lactobacillus paracasei*, *Lactobacillus farcimini*,	Salleh et al. [37]
Balik Pulau, Penang (Malaysia)	*Fructobacillus durionis*, *Lactobacillus plantarum*, *Lactobacillus fructivorans*, *Leuconostoc dextranicum*, *Lactobacillus collinoides*, *Lactobacillus paracasei*, *Leuconostoc mesenteroides*	Chuah et al. [41]
Serdang, Selangor D.E. (Malaysia)	*Lactobacillus plantarum* *Lactobacillus brevis* group, *Leuconostoc mesenteroides*, *Lactobacillus mali*, *Lactobacillus fermentum* unidentified *Lactobacillus* sp.	Leisner et al. [10]
Serdang, Selangor D.E. (Malaysia)	*Lactobacillus durianis sp.nov*	Leisner et al. [44]
Pasar Tani Kuantan, Pahang (Malaysia)	*Lactobacillus* *Fructobacillus* *Zymobacter* *Leuconostoc* *Sutterella* *Fusobacterium* *Prevotella 9*	Musa et al. [45]
Malaysia	*W. paramesenteroides*, *E. faecalis*, *E. gallinarum*, *L. plantarum*, *L. brevis*, *L. fermentum*, *L. mali*, *L. mesenteroides*, *L. casei*, *P. acidilactici*	Ajibola et al. [36]

fermentation of fermentable carbohydrates, leading to the generation of lactic acid [36]. This, in turn, can result in a decrease in sweetness and taste as sourness and acidity levels rise.

Lactic acid bacteria produce organic acids such as acetic acid, propionic acid, and butyric acid during fermentation, which add to the tangy and sour flavor [52]. The breakdown of amino acids by bacteria during

fermentation can result in the formation of taste molecules such as aldehydes, ketones, and esters, which contribute to the particular scent and flavor [52]. Microorganisms breaking down proteins during fermentation might result in the creation of peptides and amino acids, which contribute to the umami flavor [52]. In tempoyak fermentation, microbes can generate enzymes that break down complex carbohydrates and proteins into simpler ones, resulting in a softer texture and greater digestibility [52].

Nutritional value of tempoyak

Traditionally fermented durians are often spontaneous and unrestrained. Consequently, the quality of the tempoyak products fluctuates due to variable natural microflora [53]. Since fermentation relies on bacteria already present in the pulp, microorganisms in fruit pulp may originate from the environment, such as dirt, plants in the garden, the hands of vendors or customers, knives, the retail setting, baskets, and cross contamination [54].

The nutritional content of tempoyak can be determined through proximate analysis. Findings of the proximate studies on durian fruit and tempoyak (Table 3) indicated a rise in moisture content and ash content. Aisyah et al. [55] ascribe the increased moisture content to the emergence of water as a consequence of bacterial metabolic activities. On the other hand, the increased ash content is caused by the addition of salt during the fermentation process because salt is high in minerals, thus increasing ash content.

Pato and Surono [16] identified variations in the nutritional content of tempoyak in terms of carbohydrates (6.279%), protein (8.099%), fat (6.645%), ash (1.834%), moisture content (74.95%), and pH (3.69). The tempoyak for this study was purchased from a traditional market in Pekanbaru, Indonesia. Variations in nutritional content are probably due to variability in durian type [29, 56], salt composition [35, 57], sterilization duration [58], and temperature and fermentation time [38]. Meanwhile, Saidin in Ho and Bhat [29] reported that 100 g of edible tempoyak contained moisture (71.1 g), protein (2.7 g), fat (2.6 g), carbohydrate (19.6 g), Ca (14 mg), P (35 mg), Fe (1.0 mg), Na (577 mg), K (470 mg), vitamin B1 (0.20 mg), vitamin B2 (0.40 mg), niacin (1.1 mg), vitamin C (0.0 mg), and carotene (69 lg).

Table 3 Proximate test results for durian and tempoyak in 100 g of dry matter

Composition	Durian (%)	Tempoyak (%)
Moisture content	14.13	15.12
Ash	4.84	27.03
Fat	3.03	2.69
Protein	7.89	6.37
Carbohydrate	70.1	48.79

Source: [55]

Understanding the nutritional value of tempoyak is vital for analyzing its potential health benefits or detriments, planning a balanced diet, and comprehending its cultural importance. Knowledge of the nutritional value of tempoyak may promote future study and development in the area of fermented foods, and eventually, lead to the introduction of new products or techniques that boost the nutritional advantages of tempoyak and other fermented foods.

Bioactive compounds in tempoyak

Bioactive chemicals are naturally occurring substances that contribute benefits to human health [59] and are present in multifarious meals, especially fermented dishes like tempoyak. It is advised that further research seeks to understand the bioactive components and possible health benefits of tempoyak.

Generally, functional foods (like tempoyak) are high in polyphenols, terpenoids, flavonoids, and unsaturated fatty acids [59]. These substances exhibit antioxidant properties and may help protect against oxidative stress and inflammation in the body [29], and fatty acids are particularly influential in maintaining cell structure and function and promoting general health and well-being [29]. Tempoyak consists of numerous minerals, including potassium, calcium, and iron [29] needed for sustaining correct body activities such as nerve transmission, muscular contraction, and oxygen transport [59]. Furthermore, tempoyak is a fermented food that includes beneficial microbes such as *L. plantarum* and *L. brevis* [10, 36, 37] that help improve digestion, maintain a healthy immune system, and boost overall gut health [36].

Physical and sensory characteristics of tempoyak

Due to the equilibrium between the sugar component of the fruit and the lactic acid generated during fermentation, tempoyak has a particular flavor and scent [13]. Tempoyak is a whitish to yellowish semi-solid material. Furthermore, the color of the tempoyak is determined by its expiry life. The new tempoyak is vibrant, ranging from white to yellow, but the ancient tempoyak will oxidize and become brown. Tempoyak sensory texture, according to consumer surveys and focus group discussions [18], is silky, finely fibrous, a little viscous like durian flesh, and slightly translucent. Tempoyak has a delicate and watery feel due to decomposing durian flesh during fermentation and the high water content (about 55–67%).

A study on sensory qualities of tempoyak [60] reported that rather transparent appearance has won

panelist approval. Panelists favor slightly liquid tempoyak over watery tempoyak for its final texture; the former has a rougher texture and the latter is more delicate. Meanwhile, customers criticized excessively soft texture.

The primary sensory qualities acquired from consumer surveys and focus group discussions in terms of aroma were tamarind, durian, alcohol, and vinegar. The sensory characteristics of durian, sour, salty, sweet, savory, and delightful were also present [41]. Tempoyak cannot be consumed as is directly owing to its physical and sensory qualities, but rather, used as a chili sauce and a seasoning for fish curry or steamed freshwater fish wrapped in banana leaf. The panelists favored tempoyak that was a bit sour, brilliant colored, perceptible durian scented, and not too watery [41]. Sugar is sometimes added to tempoyak to heighten the sensory sensation because sugar provides a balance between sweet and sour impressions in tempoyak. According to Chuah et al. [41], tempoyak with additional 2.5% sugar was the most appreciated by the panelists with a "like" sensory score. It was also reported that the longer the tempoyak fermentation, the lower the preference level for color, flavor, and scent and the overall acceptability.

Processing technologies before probiotic microbial fermentation in tempoyak production

Various processing strategies had been utilized for probiotic microbial fermentation in making tempoyak, including the solid-state fermentation (SSF) where durian pulp is combined with salt and let to ferment in a confined container [61] to allow microorganisms grow on a solid substrate to create diverse metabolites, including enzymes, organic acids, and taste compounds [62] in the lack or near absence of free water [63].

Tempoyak fermentation is carried out under anaerobic circumstances, meaning lack of oxygen [11]. This is performed by firmly closing the lid of container for fermentation to enable the microorganisms to grow and create fermentation products [14]. In fermentation process, the optimum development and activities of microorganism rely on the perfect temperature regulation [38], namely 28–34 °C [61].

Fermentation duration may vary depending on variables such as the desired taste and texture of the finished product [38]. In general, tempoyak is fermented for 3–7 days, allowing the microbes to completely flourish and generate the unique tastes and fragrances [60]. These procedures, together durian distinctive features and specific strains of microorganisms for fermentation, have led to the peculiar taste and characteristics of tempoyak [63].

Role of ingredients to make tempoyak

The ingredients to make fermented tempoyak play crucial roles in the process. As the major component, ripe durian fruit offers sugar and nutrients needed by the microbes to develop and generate lactic acid and other chemicals [29]. Carbohydrates in durian flesh are transformed into lactic acid during the fermentation process, which gives tempoyak its unique sour and a little sweet flavor [18, 64]. Durian flesh also contains a range of beneficial vitamins and minerals, including vitamin C, potassium, and iron [29], and are rich in critical macronutrients and micronutrients and contain a high level of minerals and vitamins [65]. In general, durian flesh is a crucial element in tempoyak fermentation and contributes to the flavor, nutrition, and health advantages of the finished product. The addition of sugar enhances bacterial growth, hence improving fermentation process [66].

Salt incorporated into tempoyak making is aimed to prevent the growth of unwanted microbes while boosting the growth of lactic acid bacteria and blocking possible pectinolytic and proteolytic enzymes that can induce p softening and subsequent putrefaction [66]. Salt stimulates plasmolysis in the plant cells and the development of a liquid phase, which generates anaerobic conditions around the submerged product [66]. This condition is more effective for finely cut and shredded materia [66]. Spices or aromatic herbs, such as turmeric, are added to most of the lactic fruits and vegetable fermentations to enhance the taste of the finished products and lengthen their shelf life [36].

Beneficial health effects of tempoyak

Indonesia is home for a vast range of functional foods (FF) that provide health advantages. Functional foods are distinguished nutraceuticals, meaning complete foods or dietary components with microvascular, anti-inflammatory, and anti-oxidizing activities in gravely afflicted individuals [59] and can prevent and/or treat illness [67].

As a functional food, tempoyak is made of fresh durian flesh that is fermented to modify its original health properties, especially improving minerals, amino acids, vitamins, antioxidants, and antibacterial properties of durian [62, 63] and antimicrobial substances (lactic acid, butyric acid, propionic acid, acetic acid, formic acid, bacteriocins, and hydrogen peroxide) [36] (Table 4).

The benefits of tempoyak as a functional food, as explained above, present an opportunity for tempoyak to improve public health quality. A previous study [72], reported that in addition to LAB, other microorganisms with good potential in Indonesian fermented foods needs to be extended, such as yeast and several Bacillus species for probiotics.

Table 4 Tempoyak functional properties for human health

Tempoyak's functional properties	Mechanisms	References
Immunostimulant	Tempoyak water extract may stimulate the secretion of cytokines in RAW 264.7 cells. RAW 264.7 cells are monocytes (macrophage-like cells) generated from Abelson leukemia virus cell-line cultures obtained from BALB/c mice. RAW 264.7 cells, which are capable of both pinosity and phytocytosis, are the appropriate models of macrophages. RAW 264.7 cells may enhance the generation of nitric oxide (NO) and the process of cell phagocytosis in response to LPS stimulation. These cells may also eliminate target cells or pathogens via antibody-dependent cytotoxicity	Susanto et al. [69] and Taciak et al. [70]
Reduce cholesterol levels (antihypercholesterolemia)	By removing 17.86% of the cholesterol from the medium, the isolates obtained from tempoyak demonstrated the ability to bind cholesterol. Thus, it may reduce the prevalence of coronary artery disease	Pato and Surono [16]
	Seven *Lactobacillus* strains of LAB from Tempoyak exhibited the capacity to remove cholesterol from the growing medium in the presence of bile salts (25.99–75.15%)	Khalil et al. [17]
Probiotic effect	Probiotic bacteria isolated from tempoyak have excellent effectiveness in acid tolerance and bile salts, antioxidants, anti-proliferation, and have the potential to inhibit the growth of the colorectal cancer cell line HT-29 Bax/Bcl-2 or NO production. Adherence of probiotic bacteria to the colonic epithelium prevents colonization by pathogenic microbes and may effectively influence the host immune system. An overview of the health advantages of probiotic LAB to the host is presented in Fig. 4	Chen et al. [15]
Reduce the formation of infections (food preservatives)	*L. buchneri* DSM 20057T isolated from tempoyak has the capacity to create sorbic and benzoic acids. Consequently, this strain viable for preservatives in food by limiting the development of harmful bacteria	Salleh et al. [37] and Chuah et al. [41]
Antimicrobial activity for pathogenic microorganism	*L. plantarum* isolated from tempoyak showed antagonistic action against the viability of *Staphylococcus aureus*. *L. plantarum* which isolated from tempoyak can produce plantaricin, which is bactericidal	Widowati et al. [71]

Challenge, future, and development of tempoyak

Challenges of tempoyak production

There are various obstacles in making and conserving tempoyak that include durian fruit availability. Durian fruit is only accessible periodically (durian season at the start or end of year) in particular regions [73], so restricted supply is the main challenge to make tempoyak all year round. Consequently, tempoyak is often manufactured during the durian season.

In terms of fermentation conditions, tempoyak is typically fermented at room temperature for 4–7 days with a minor quantity of salt [11], so tampering with the temperature can lead to unfavorably uneven quality. Another contributing factor is the dearth of standardization, where no standardized methods are established presently for producing and preserving tempoyak, thus contribute to variations in the quality and safety of the final products [74]. At the market end, consumers will find it difficult to ascertain of the quality of tempoyak they purchase.

The fermentation process of tempoyak involves the growth of lactic acid bacteria (LAB) and other microorganisms [18] and rely on autochthonous microbes present in durian flesh [45]. Improperly controlled conditions for fermentation can allow harmful microorganisms to grow and contaminate the product.

Tempoyak has a short shelf life due to its high moisture content and the growth of microorganisms during storage [43]. This makes it difficult to transport and distribute tempoyak to regions where durian fruit is not readily available.

Overall, the production and preservation of tempoyak face several challenges related to the availability of durian

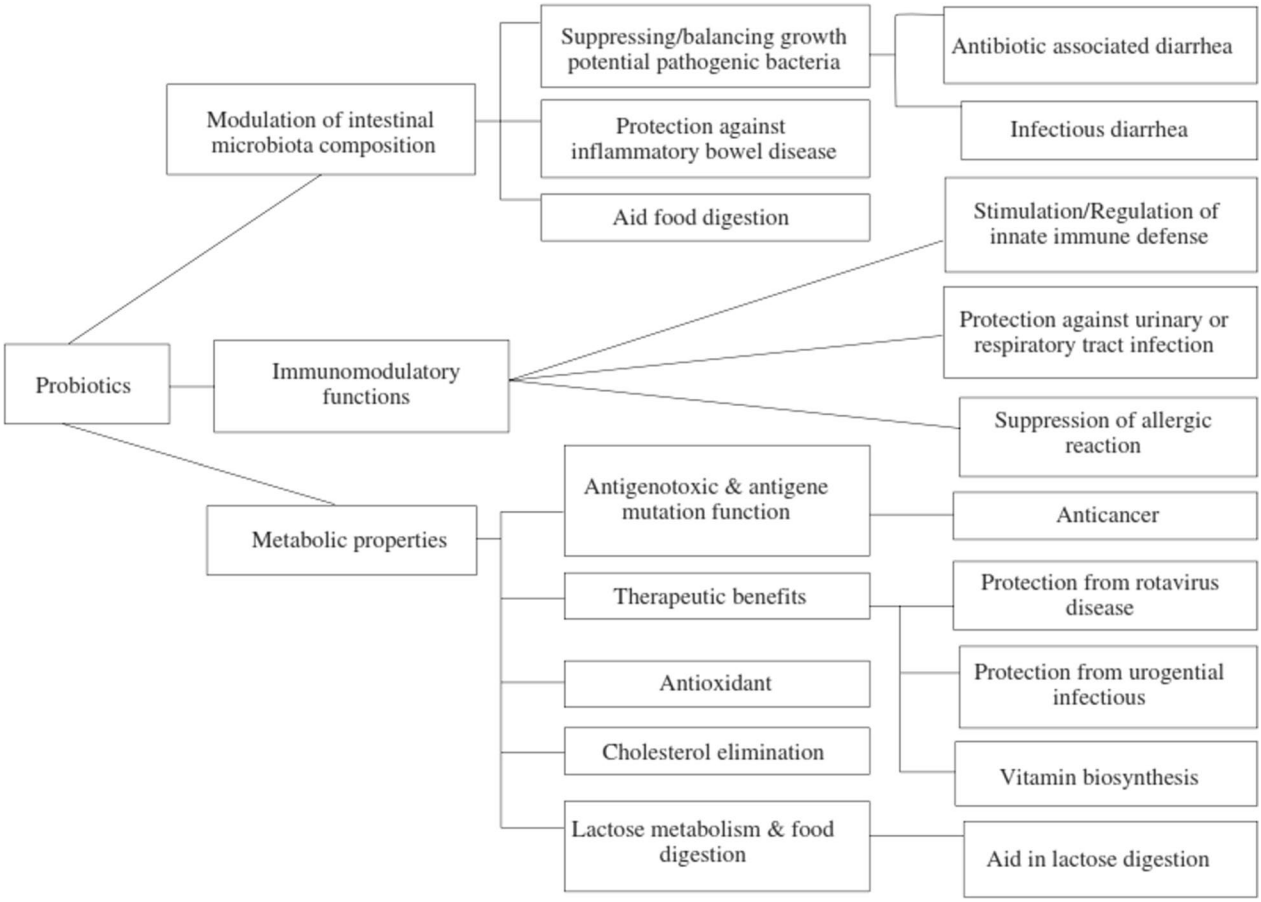

Fig. 4 Health benefits of probiotic LAB in fermented tempoyak (*Source*: [36])

fruit, fermentation conditions, microbial contamination, shelf life, and lack of standardization. To solve these issues, it is vital to establish appropriate tempoyak manufacturing methods, including sufficient sanitation, quality control, and safety precautions. The introduction of probiotic strains of lactic acid bacteria may help increase the quality and safety of tempoyak [9, 66, 75]. Additionally, research on the optimization of fermentation conditions and the utilization of alternate sources of durian fruit might assist increase the production and supply of tempoyak. Addressing these challenges could help improve the quality and safety of tempoyak and make it more widely available to consumers.

Future and development of tempoyak

The future and development of tempoyak contain various possible prospects and advancements. As consumers has increasingly valued health and wellbeing, interests in functional foods and components also grow. Tempoyak, with its potential health advantages and unusual taste profile, can be a functional food that not only exhibits nutritional value but also a novel gastronomic experience. The main opportunity in developing tempoyak is the promising source of of probiotics [28] immunostimulant, antihypercholesterolemia [16], preservatives [37], and antibacterial properties [71]. Further study is required to better understand the unique health advantages of tempoyak and its bioactive components and promote better marketing of tempoyak as a functional food by highlighting evidence-based claims for its health impacts.

Reflecting on the multiple benefits above, there is potential to expand tempoyak commercial reach and appeal to a larger audience given the increased desire in its distinctive and exotic tastes. Innovations have advocated the potentials to increase tempoyak diversity and quality. Previous studies has attempted to pulverize dried tempoyak into flour to increase its shelf life, facilitate product distribution, and reduce the sour smell of fresh tempoyak [76]. Reli et al. [43] improved the quality of tempoyak flour by incorporating maltodextrin as a food filler to retain the texture and flavor of tempoyak, which may change in the drying process.

Durian, the primary component in tempoyak, is a resource-intensive fruit that demands precise cultivation

and harvesting procedures. To maintain the long-term supply of durian and sustainable tempoyak production, efforts should be taken to encourage responsible sourcing and production practices.

To ensure the authenticity and quality of tempoyak, it is vital to create and enforce standards for its production, including fermenting procedures, ingredient procurement, and hygiene measures. This may help safeguard the reputation of tempoyak as a traditional Indonesian delicacy and assure constant product quality. It is highly encouraged to produce tempoyak with the addition of an inoculum commencing culture for a more controlled approach. The use of pure culture starter in a tempoyak fermentation technique lowers contamination because its presence at the outset of fermentation slows the growth of contaminating bacteria [39].

Increasing tempoyak appeal to a bigger worldwide audience, efforts should be made to market tempoyak as a unique Indonesian product, highlighting its cultural value, health advantages, and culinary variety. Tempoyak marketing strategy can be boosted further with a longer shelf life by altering the pasteurization technique and improving packages using the modified atmosphere packing (MAP) [77]. According to Silvestre et al. [78] and Watts [79], pasteurization is a heating process that extends the shelf life of food by heating it to a temperature of 60–100 °C, in order to kill microorganisms such as bacteria, fungi, and yeast, and deactivate enzymes [77] contained in the food while maintaining its quality. Meanwhile, Sugiyanti [77], reported that MAP is a food packaging method that extends the expiration life of food commodities by inhibiting circulation while enabling the product to breathe properly, reducing the oxygen concentration in the air within the package, and raising the carbon dioxide level.

Continued research and innovation in tempoyak production, processing, and product development could help uncover new possibilities and overcome obstacles. This involves investigating innovative fermentation processes, ingredient combinations, and packaging options to increase the quality, shelf life, and consumer appeal of tempoyak products.

Conclusion

Tempoyak, a fermented durian paste, is a well-known delicacy among the Malay ethnic community in Indonesia. It symbolizes a unique and culturally important culinary item among other varieties of Indonesian cuisine. The fermentation process of tempoyak involves lactic acid bacteria (LAB) that contribute to its distinctive taste and texture. Tempoyak has been discovered to contain high probiotic properties, including acid and bile salt tolerance, antioxidative and anti-proliferative activity, and outstanding adherence to the Ht-29 colon cancer cell line. These potential health advantages have put tempoyak under the spotlight of research on functional foods, nutraceuticals, food microbiology, and fermentation. The nutritional content of tempoyak, including carbohydrates, protein, fat, ash, and moisture, has been examined and offered insights on tempoyak composition and possible dietary contributions. Future study can seek to produce innovations such as tempoyak flour, which may enhance tempoyak shelf life, simplify product distribution, and minimize its sour flavor. This feature of tempoyak production is significant to the subject of food science and technology. Tempoyak is not only a tasty and distinctive condiment but also a versatile source of health benefits. Consuming tempoyak may lead to a better understanding of the linkage between food, culture, and human well-being.

Acknowledgements
The author would like to deepest thank all parties who have helped in the completion of this research.

Author contributions
All authors had equal contributions as the main contributors to this manuscript paper. First, second, third, fourth and fifth authors contributed for the literature searching and manuscript writing. All authors read and approved the final manuscript.

Funding
There is no funding resource could be reported for this publication.

Availability of data and materials
Not applicable.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
All authors agree for this publication.

Competing interests
All authors declare there is no competing interest regarding this publication.

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Received: 14 April 2023 Accepted: 22 October 2023
Published online: 01 December 2023

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