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History, manufacture, nutritional content, bioactive compounds, and health benefits of tempeh and tofu as alternative protein in Indonesia: a review

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Abstract. This article reviews the historical background, production processes, nutritional composition, bioactive compounds, and health benefits of tempeh and tofu as alternative protein sources in Indonesia. Tempeh and tofu are popular plant-based proteins integral to Indonesian cuisine for centuries, offering a sustainable and nutritious alternative to animal proteins. Tempeh, a fermented soybean product, is rich in proteins, essential fatty acids, vitamins, and minerals. At the same time, tofu, made from coagulated soy milk, provides a complete amino acid profile and is low in carbohydrates. The fermentation process enhances the bioavailability of nutrients in tempeh, making it a functional food with health benefits, including digestive and cardiovascular health booster and potential anti-cancer properties. Tofu, with its bioactive peptides, offers antioxidative and anti-inflammatory effects, contributing to overall health. This review also highlights the potential of tempeh and tofu in addressing Indonesia's growing protein needs and sustainability challenges, through innovative products promising economic and nutritional benefits.

Keywords: tempeh; tofu; plant-based protein; fermentations; and bioactive compound

Introduction

Recently, the use of alternative proteins has been proliferating worldwide. The growing demand for alternative protein sources in the global food market is driven by the combination of environmental, health, and economic factors. Traditional animal-based protein production is associated with high greenhouse gas emissions, significant land and water use, and potential health risks due to high lipid content. Livestock production is a major contributor to greenhouse gas emissions and environmental degradation. Alternative proteins, such as plant-based proteins, offer a more sustainable option with a lower carbon footprint (Manikandan et al., 2024; Macêdo de Medeiros et al., 2024). The efficient use of resources in alternative protein production, such as lower land and water use, supports global efforts to mitigate climate change impacts (Erol and Demir, 2024). Traditional animal proteins are often high in fat but low in fiber, posing health risks. Alternative proteins, particularly plant-based options, provide healthier nutritional profiles (Manikandan et al., 2024). The inclusion of legumes and other plant-based proteins in diets can enhance nutritional intake while supporting health and wellness (Büyüktuncer and Özdemir, 2024). Some innovations in food technology and biotechnology, such as fermentation technology, improve the quality and reduce anti-nutritional contents in plant-based proteins, leading them more viable for consumption (Manikandan et al., 2024). Furthermore, economic prospects for alternative proteins are promising due to their affordability and potential to reach price parity with traditional proteins (Macêdo de Medeiros et al., 2024).

Due to its large population, Indonesia faces a growing demand for protein, requiring higher agricultural productivity and more diverse alternative protein sources (Sari et al., 2021). Plant-based protein has been extensively utilized in Indonesia as source of protein. The country's diet is characterized by a significant proportion of plant-based proteins, particularly legumes, beans, and cereals, accounting for 65.4% of total protein sources (Khusun et al., 2022). However, this high consumption of plant-based proteins is associated with lower socio-economic status and is more prevalent in rural areas (Khusun et al., 2022).

Regarding alternative protein sources, Indonesia has a long history of including plant-based proteins like tempeh and tofu into cuisine. This tradition supports the integration of alternative proteins into local diets. Tempeh and tofu are Indonesia's most popular plant-based protein sources (Purwadaria et al., 2016). They are deeply ingrained in Indonesian cuisine and widely consumed nationwide.

Tempeh is particularly significant in Indonesian culture, with over 100,000 producers and a long history dating back to the 1700s (Surono, 2016); (Purwadaria et al., 2016). Tofu is also widely consumed and is often eaten with rice and sweet soy sauce (Astuti et al., 2023). Both tempeh and tofu are rich in protein and are considered staples in Indonesian diets. They are versatile and can be used in various dishes, from simple fried tempeh to more complex recipes. The popularity of tempeh and tofu is evident in their widespread consumption and the variety of dishes that incorporate them (Mozaic, 2023).
This paper will discuss tempeh and tofu as alternative proteins in Indonesia, inlcuding the history, production processes, nutritional composition, bioactive compounds, health benefits, and prospects as contemporary alternative proteins.

History of tempeh and tofu in Indonesia

Introduction of soybeans
The origin of tempeh and tofu in Indonesia can be traced back to the introduction of soybeans. Soybeans were introduced to Indonesia via trade with South China around 1000 AD, signifying the start of soybean production and usage in Indonesia (Hartati, 2021).
Soybeans are a leguminous crop that originated in China and were introduced to Indonesia via commerce. They are indigenous to mainland China and have been intentionally grown since 2500 BC. The factory expanded to other countries because of the growing commercial relations between nations in the early 19th century, reaching many trade destinations, including Japan, Korea, Indonesia, India, Australia, and America.
Several papers reported the first soybean introduced into Indonesia. Hasbianto et al. (2020) stated that soybeans have been a part of Indonesian traditional cuisine since the 12th century. Soybeans have been documented in Indonesia since the 15 – 16th century (Hymowitz, 1990). However, Sumarno (2015) stated that soybeans have been grown in Indonesia since 1746 for rice crop rotation on wetlands by applying indigenous technology. The spread and cultivation of soybeans originated in Java and then expanded to Bali, Nusa Tenggara, and other neighboring islands.

Development of tempeh
Tempeh originated in Indonesia, particularly in Central or East Java. Its precise genesis may be traced back centuries, perhaps even millennia. The tempeh fermentation process utilizes the *Rhizopus oligosporus*, which is believed to have been inspired by traditional Chinese soy sauce manufacturing methods (Romulo and Surya, 2021). Tempeh, a meal that has become a staple in Indonesia, is made using indigenous Javanese soybeans and traditional fermenting techniques.
Tempeh, a fermented soybean product, was first mentioned in the *Serat Centhini* manuscript, which documents the reign of Sultan Agung from Mataram, a region in Java – part of Nusantara, currently known as Indonesia. This information is derived from the History of Tempeh and Tempeh Product (1815 – 2011) published by the Soyinfo Center in 2011. According to the documents, tempeh has existed in Java since 1600s (Shurtleff and Aoyagi, 1985).

Introduction of tofu
Tofu is another popular soy-based product in Indonesia. It is often eaten with rice and sweet soy sauce. It is widely consumed and is known for its versatility in various dishes (Wicaksono and Yuguslavia, 2018).
Tofu was introduced to Java by Chinese traders around the 17th century. During that period, it gained widespread recognition and started to be embraced by the local people. Tofu is derived from the Chinese Indonesian term "*tahu*' or "*takua*" (tofu), which refers to a kind of cuisine (Kusumaningtyas et al., 2021). Due to the limited availability of livestock on densely populated Java Island, tofu became a popular alternative to meat products.

Tempeh and tofu during the Dutch colonial period
Under Dutch colonialism, the implementation of forced cultivation program resulted in widespread reforestation and a scarcity of food resources, leading the local inhabitants to consume tempeh and tofu.
As people migrated from Java to other areas, the popularity of tempeh increased, and it underwent modifications to suit local preferences, resulting in the emergence of regional varieties such as *tempe mlanding*, *tempe benguk*, *tempe gembus*, and *tempe bongkrek* (Romulo and Surya, 2021). Tempeh and tofu were produced massively as a response to the limited availability of livestock and the need for alternative protein sources.

Tempeh and tofu in 60s, 70s, and 80s
In the mid-1970s, soy tempeh constituted almost 90% of Indonesia's production. The manufacturing of tempeh and tofu experienced significant growth and variation throughout the late 1960s and early 1970s. Polyethylene bags and wooden trays replaced banana leaves. The fermentation was enhanced by developing a semi-pure culture inoculum using cooked rice.

Tempeh and tofu in recent era
Tempeh and tofu manufacturing have seen significant advancements in recent years. The Indonesian Tempeh and Tofu Producer's Cooperative (PUSKOPTI) has promoted the establishment of over 100,000 tempeh and tofu producers in different regions across Indonesia. New variants, such as *tempeh bongkrek*, manufactured from soybeans and coconut pulp, have been introduced.
Notwithstanding the expansion and broadening of the sector, obstacles continue to exist. The recent strike led by PUSKOPTI members underscores the impact of the surging soybean process on the manufacturing and distribution of tempeh and tofu.

The industry is susceptible to both supply chain interruptions and economic volatility. To tackle these difficulties, enhancing supply chain management and fostering technological cooperation is essential to guarantee the sector's long-term viability.

Production and consumption of tempeh and tofu in different regions

Production of tempeh in different regions

Indonesia: Tempeh is a traditional and staple food in Indonesia, produced through the fermentation of soybeans by *Rhizopus* spp. It is widely consumed across the country, with around 80,000 small and medium producers, processing over 1 million tonnes of soybeans annually (Teoh et al., 2024; Wiloso et al., 2019). The production methods vary. Traditional methods often involve manual processes and local sales, while modern methods incorporate advanced technology and digital marketing to enhance production capacity and market reach (Wisnujati et al., 2024; Putri et al., 2024). The environmental impact of tempeh production in Indonesia is significant, and the transportation of soybeans being a major contributor to greenhouse gas emissions (Wiloso et al., 2019; Putri et al., 2024).

Malaysia: Similar to Indonesia, tempeh is also commonly produced in Malaysia, where it is valued for its high protein content and health benefits (Teoh et al., 2024).

Denmark: In Denmark, tempeh is relatively unknown but has the potential as a high-quality protein source. A survey indicated that only 2.6% of consumers knew tempeh, thus its introduction to the market would require increased consumer education and marketing (Aaslyng and Højer, 2021).

West to Northcentral Africa: Tempeh production involves local legumes like Zamnè, which are fermented to improve their nutritional value and digestibility. This adaptation aims to mitigate the hard-to-cook defects of these legumes and promote their use in human diets (Drabo et al., 2023).

Consumption of tempeh in different regions

Indonesia: Tempeh is a staple food and consumed widely across regions. It is an essential part of the diet, providing a significant source of non-meat protein (Wiloso et al., 2019; Setyawan et al., 2023). The consumption patterns are influenced by regional variations in the microbiota of tempeh, which affects the flavor and quality (Wicaksono et al., 2024).

Malaysia: Similar to Indonesia, tempeh is a common part of the diet, appreciated for its nutritional benefits (Teoh et al., 2024).

Denmark: The consumption of tempeh is limited but growing. Consumers who are familiar with tempeh tend to have positive attitudes towards it, especially when it is presented as a unique food item rather than a meat substitute (Aaslyng and Højer, 2021).

West to Northcentral Africa: The introduction of tempeh made from local legumes like Zamnè is aimed at improving diet and nutrition in regions prone to drought and hunger (Drabo et al., 2023).

Production of tofu in different regions

Asia: Tofu is a major dietary staple in Asian countries, particularly in Indonesia and Japan. In Indonesia, tofu production is widespread across all provinces and primarily carried out by micro, small, and medium enterprises (MSMEs) (Erliana et al., 2023). The production in Indonesia involves several stages, including soaking, washing, filtering, grinding, boiling, cooking, pressing, and cutting (Astuti et al., 2020). The industry faces challenges such as high energy and water consumption, and significant wastewater (Ningsih et al., 2024). Cleaner production strategies and more strict energy audits are recommended to improve efficiency and environmental impact (Ningsih et al., 2024; Septifani et al., 2021; Herdhiansyah, et al., 2022).

North America: The consumption of tofu is increasing in North America due to its health benefits. Efforts are being made to develop high-quality tofu cultivars adapted to North American conditions by utilizing diverse soybean accessions (Kim et al., 2008). In the production, appropriate soybean varieties are selected and specific coagulants are used to ensure high-quality tofu (DePalma et al., 2019).

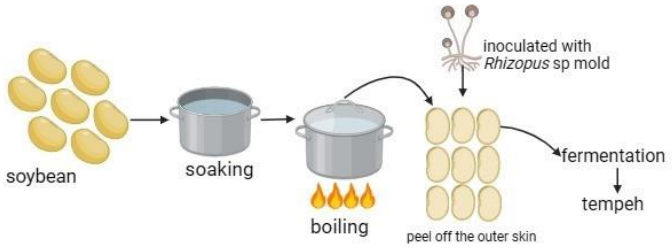
Consumption of tofu in different regions

Asia: Tofu is highly favored in Asia, with significant consumption in countries like Indonesia which was about 0.15 kg/person/week in 2017 (Septifani et al., 2021). Consumption patterns are influenced by income levels, and higher-income households show varied likelihoods of consuming tofu. Tofu is popular due to its high nutritional value and affordability (Erliana et al., 2023).

North America: The consumption of tofu is steadily increasing in North America, driven by its health benefits and the growing popularity of plant-based diets. Efforts to produce hypoallergenic soybeans and improve tofu quality are ongoing to meet consumer demand (Kim et al., 2008).

Table 1. Bioactive compounds in tempeh and its health benefits on the human body

No.	Bioactive compounds	Its health benefits	Ref.
1	Isoflavones, saponins, and amino acids	Antioxidant, antihypertensive, and antidiabetic properties, contributing to improved health	(Sinaga and Tumewu, 2023)
2	Organic acids, antioxidants, and antimicrobial compounds	Enhance nutritional value, increase vitamin content, and contribute to health benefits like antidiabetic and cholesterol-lowering effects	(Teoh et al., 2024)
3	Isoflavones	Antioxidant properties reduce ROS levels and boost antioxidant enzyme expression, enhancing its health benefits	(Athailah et al., 2019)
4	Flavonoid compounds: genistein, genistin, daidzein, and daidzin	Prolonged fermentation enhances their release, contributing to health benefits like cytotoxic activity against cancer cells	(Surya et al., 2021)
5	γ-aminobutyric acid (GABA) and anthocyanin	Reducing oxidative stress inflammation and enhancing brain-derived neurotrophic factor (BDNF) expression	(Hwang et al. 2019)
6	Isoflavones, proteins, and peptides	Reducing body weight, lowering body fat, and improving lipid profile are beneficial for treating obesity	(Astawan et al., 2018)
7	Isoflavones, folic acid, vitamin B12, and magnesium	Brain health and prevention of chronic diseases	(Mani and Ming, 2017)
8	Bioactive peptides	Antihypertensive, antidiabetic, antioxidative and antitumor properties	(Tamam et al. 2019; Tamam et al., 2021)
9	Polyunsaturated fatty acids (PUFAs) like omega-3, linoleic acid, and isoflavones	Antioxidant properties and potential health benefits	(Limanjaya et al., 2022)
10	Daidzein and genistein aglycones	Exhibit enhanced BACE 1 inhibition and antioxidant activities compared to soybean, and offering health benefits	(Ahmad et al., 2015)



[A]

[B]

Figure 1. The essential stages of tempeh [A] and tofu [B]'s production. Created by: https://BioRender.com

Table 2. Bioactive compounds in tofu and its health benefits on the human body

No.	Bioactive compounds	Its health benefits	Ref.
1	Isoflavones, like genistein and daidzein, along with phenolic compounds, and terpenoids	Antioxidant and contributing to prevent cancer and cardiovascular disease	(Punoo et al., 2024)
2	Bioactive peptides, like lunasin and soymorphins	Hypolipidemic, anti-hypertansive, anti-cancer, anti-inflammatory, antioxidant, and immunomodulatory properties	(Sheneni and Momoh, 2023)
3	Bioactive peptides derived from soy proteins	Antihypertensive, immunomodulatory, and antioxidative effects, aiding in chronic disease prevention	(Abedin et al., 2022; Oh et al., 2022)
4	Isoflavones	Regulate the intestinal environment, particularly aiding in constipation relief and overall gut health	(Oh et al., 2022)
5	Isoflavones, like genistein, daidzein, and glycitein	Cancer reduction, menopausal symptom relief, and cardiovascular health	(Bachanek et al., 2017)
6	Isoflavones, phenolic acids, and calcium	Reducing in menopause symptoms, reducing cancer and heart desease risks, and osteoporosis prevention	(Riciputi et al., 2026; Ke and Watson, 2013)
7	Isoflavones, saponins, phytates, protease inhibitors, phenolic acids, and lecithin	Anti-cancer, antioxidant effects, and prevent cardiovascular disease	(Liu and Pan, 2011)
8	Isoflavones, like daidzin, genistin, daidzein, and genistein, glycitein	Estrogenic and antioxidant properties, promising dietary source	(Rekha and Vijayalakshmi, 2010; Yanguo et al., 2020; Jou et al., 2013)
9	Peptides	Antioxidative and ACE inhibitory activities	(Zaheer and Akhtar, 2017; Wang et al., 2003)

Figure 2. Picture of tempeh [A] and tofu [B].

Global consumption: Tofu has been consumed globally, with significant popularity in vegetarian, vegan, and hypocaloric diets (Kim et al., 2008). The production and consumption of tofu are influenced by regional availability of raw materials, environmental considerations, and consumer preferences.

Manufacturing of traditional tempeh and tofu

Manufacturing of tempeh

Tempeh is a traditional Indonesian cuisine derived from soybean seeds (Dwiatmaka et al. 2021). The optimal procedure for manufacturing tempeh has been documented in several scientific articles and patents (Dwiatmaka et al., 2021; Hachmeister and Fung, 1993; Han, 2009; Tomohiro et al. 2005; Fujisawa, 2003; Shi, 2018). The essential stages for producing tempeh are first, soaking soybean seeds, then cooking them, and introducing *Rhizopus* fungus to allow fermentation, which can be seen in **Fig. 1A**. Soybeans in their natural state are organized and immersed in water for 24 hours at normal room temperature to restore their moisture and facilitate further processing. After soaking, the soybeans undergo a thorough

washing to eliminate any contaminants, and subsequently, the outer skin is peeled off. This process aims to diminish the bitterness of the soybeans and enhancing their smoothness. Subsequently, the soybeans are subjected to boiling or steaming for 30 to 60 minutes. Cooking helps to decompose some intricate chemicals in soybeans, making them more amenable to fermentation. The soybeans undergo a cooling and drying process after being cooked to eliminate any surplus moisture. This phase is essential for establishing a favorable environment for fungal proliferation. After chilled and dried, the soybeans are treated with a starting culture containing *Rhizopus oligosporus*, a special fungus for tempeh (Mozaic, 2023). This culture is often derived from dehydrated spores of *Rhizopus oligosporus*. The soybeans treated with inoculants are covered with perforated plastic banana leaves to allow for proper air circulation and maintain moisture levels. The packaged soybeans are placed in an environment of around 25-30ºC and left to incubate for 48 hours. During this period, the *Rhizopus oligosporus* fungus proliferates and consolidates the soybeans into a dense cake. The soybeans are subjected to a natural fermentation process that lasts for a maximum of 48 hours. During this phase, the fungus decomposes some intricate molecules in the soybeans, rendering them more readily digested and enhancing their nutritional values. The picture of tempeh after fermentation which can be found in traditional market in Indonesia, and is ready to cook can be seen in **Fig. 2A**.

Producers can prolong the fermentation period beyond 48 hours, which might lead to over-fermentation. Tempeh, which has undergone excessive fermentation, has a discernible brown hue, texture, and taste, and is often used as a condiment in Indonesian.

Once the fermenting process is complete, the tempeh is collected and may be consumed. It may also be kept in the refrigerator to extend its freshness. The prolonged process of fermentation tempeh until 72-96 hours over maturity, well known as *tempeh semangit* could enhance the digestibility and bioavailability for the consumers. Kusumawaty et al. (2020) developed supplementary food for women in pregnancy to prevent newborn stunting and found that *tempeh semangit* has higher amino acid content than common tempeh.

Manufacturing of tofu

Several research articles and patents document the techniques of tofu manufacturing (Watanabe, 1998; Masaru et al., 1999; Hiroaki and Shiraiwa, 2001; Tomohiko et al., 2001; Asai, 2005; Gi et al., 2010; Wang et al. 2011; Yeon, 2012; Jingang, 2012; Togashi et al., 2016; Soub et al., 2019; Kwi, 2020; Darmajana et al., 2020; Sudarminto and Elok, 2020; Li et al., 2017). The essential stages of tofu production can be seen in Fig. 1B. The procedure starts by immersively rehydrating soybeans in water for 8 to 12 hours. Rehydrating the soybeans facilitates their processing. The soybeans undergo thorough washing to eliminate contaminants after soaking. The washing procedure must be meticulous to get high-quality tofu. Next, the soybeans are pulverized into a smooth paste using a grinding mill. This stage is essential for achieving a homogeneous mixture. Subsequently, the soybean paste is subjected to boiling water, resulting in soy milk. In this procedure, the temperature of the mixture is raised to denature the soy proteins, rendering them more amenable to coagulation. Once the soy milk has been boiled, it is filtered to eliminate leftover soybean solids. This stage clarifies the mixture and makes it ready for coagulation. A coagulant, usually calcium sulfate or magnesium chloride, aims to induce curdling in soy milk. The mixture is left for some time, facilitating the formation of curds. Afterwards, the curd is compressed into a solid form using cheesecloth or a tofu mold. This stage eliminates surplus moisture and imparts the required texture to the tofu. To ensure the tofu's freshness, it is packed in airtight containers. Tofu is available in fresh or frozen form, depending on its intended use. The picture of tofu in a traditional market in Indonesia can be seen in Fig. 2B.

Nutritional composition of tempeh and tofu

Macro and micronutrients of tempeh

Tempeh is a highly nutritious fermented food primarily made from soybeans, well known for its rich nutrient profile. Key nutrients in tempeh include high-quality plant-based protein, reported ranging from approximately 30% to 31% per 100 grams, depending on the bean combination used (Tan et al., 2024). Additionally, tempeh contains essential fatty acids, with a total fat content of around 9% to 10% (Tan et al., 2024). Tempeh contains about 12% to 16% carbohydrates, contributing to its energy content (Tan et al., 2024). It is also a good source of dietary fiber, with values around 4% to 11% (Tan et al. 2024).

Tempeh is also a notable source of vitamin B12, which is particularly beneficial for plant-based diets (Rosalina et al., 2024). The fermentation process enhances the bioavailability of nutrients, producing beneficial metabolites such as organic acids and antioxidants, although its antioxidant capacity is lower than that of vitamin C (Evangelista and Surya, 2024). Furthermore, tempeh provides minerals (including calcium, potassium, and iron), and various amino acids, leading it as a valuable plant-based protein source (Švarc et al., 2022; Nuraida, 2019). Tempeh's diverse nutrient composition supports its role as a healthy dietary option.

Macro and micronutrient of tofu

Tofu is a highly nutritious plant-based protein source, rich in essential amino acids, particularly compared to other plant proteins. It typically contains about 8 grams of protein per 100 grams, making it a staple in vegetarian and vegan diets (Anjum et al., 2023). It contains healthy fats, primarily polyunsaturated and monosaturated fats, ranging from 4 to 5 grams per 100 grams (Anjum et al. 2023). Tofu has a low carbohydrate content, typically only around 1.9 grams per 100 grams,

contributing to its low glycaemic index (Anjum et al. 2023).
Tofu is an important source of essential minerals such as iron (up to 19.5 mg/kg), calcium, magnesium, and zinc (Paz et al., 2021). It also contains trace elements like cobalt, chromium, and selenium, contributing to daily nutrient intake (Syahfitri, 2020). While tofu is not a major source of vitamins, it does contain some B vitamins, which are crucial for energy metabolism (Jung and Kim, 2016).
Compared to other plant-based proteins, such as legumes and grains, tofu offers a more complete amino acid profile, which is crucial for the health especially muscle repair (Paz et al., 2021). While legumes like lentils and chickpeas are also high in protein, they often lack certain essential amino acids that tofu provides (Syahfitri et al., 2020). However, it is important to note that the nutritional benefit of tofu can vary based on its preparation method and the presence of other ingredients in a meal. Overall, tofu stands out as a versatile and nutrient-dense option within the spectrum of plant-based proteins, supporting a balanced diet (Paz et al., 2021; Syahfitri et al., 2020; Jung and Kim, 2016).

Bioactive compounds and their health benefits in tempeh and tofu

Bioactive compounds and health benefits of tempeh

Tempeh, a traditional Indonesian fermented soybean product, is rich in bioactive compounds that offer various health benefits, as can be seen in **Table 1**. Tempeh's bioactive compounds have anti-oxidant, anti-inflammatory, neuroprotective, and anti-cancer effects. Thus, it can prevent chronic diseases, improve bone health, and support gut health. Further research and clinical trials are warranted to fully understand and confirm these health benefits in humans. These compounds include isoflavones, γ-aminobutyric acid (GABA), anthocyanins, and bioactive peptides, which contribute to tempeh's antioxidative, anti-inflammatory, and neuroprotective properties. Key compounds including isoflavones, saponins, and amino acids, exhibit antioxidant, antihypertensive, and antidiabetic properties (Nuraida, 2019; Sinaga and Tumewu, 2023).

Antioxidant properties

Isoflavones: Tempeh contains high levels of isoflavones, which exhibit significant antioxidant activities. Studies have shown that tempeh extracts can boost the expression of antioxidant enzymes such as catalase and superoxide dismutases (SOD2 and SOD3) in HepG2 cells, thereby reducing oxidative stress and protecting cells from damage (Surya and Romulo, 2020; Surya et al., 2021). Furthermore, tempeh extracts have shown the ability to reduce oxidative stress by upregulating antioxidant enzymes, indicating a protective role against cellular damage (Surya et al. 2021).
Phenolic compounds: The fermentation process enhances the total phenolic content in tempeh, boosting its antioxidant capacity to be higher compared to non-fermented soybean (Surya et al., 2021).

Anti-inflammatory and neuroprotective effects

GABA and anthocyanins: Tempeh, especially when fermented with *Rhizopus* and *Lactobacillus*, contains high GABA and anthocyanins concentrations. Compounds like γ-aminobutyric acid (GABA) and anthocyanins in certain tempeh varieties have also demonstrated neuroprotective effects (Hwang et al., 2019). These compounds have been shown to reduce oxidative stress and inflammation in BV-2 microglial cells, downregulate nitric oxide synthase, and upregulate brain-derived neurotrophic factor (BDNF), which is crucial for neuroprotection and cognitive function (Hwang et al., 2019).
Bioactive peptides: The fermentation produces bioactive peptides that have anti-inflammatory properties, which can modulate immune responses, contributing to overall health benefits (Rizzo, 2024).

Chronic disease prevention

Cardiovascular Health: The consumption of tempeh is linked to reduced risk of cardiovascular diseases due to lipid-lowering and antihypertensive effects. The bioactive compounds in tempeh help regulate blood levels and improve vascular function (Mani and Ming, 2017; Ortega and Campos, 2019).
Cancer Prevention: Isoflavones in tempeh, such as daidzein and genistein, have shown potential anticancer properties by inducing apoptosis and inhibiting cancer cell proliferation. These compounds are particularly effective against breast cancer cells, making tempeh a promising functional food for cancer prevention (Nurkolis et al., 2024). Notably, isoflavones like genistein and daidzein have been linked to cytotoxic effects against cancer cells, with concentrations varying based on fermentation time (Athaillah et al. 2019).
Bone Health: Tempeh, combined with probiotics like *Lactobacillus acidophilus*, can improve bone health by enhancing calcium absorption and bone metabolism, which is beneficial for post-menopausal women at risk of osteoporosis (Harahap et al., 2024).

Gut health and digestibility

Probiotics: Consuming tempeh has been associated with various health benefits, including digestive health improvement due to its high fiber content, and heart health enhancement through cholesterol-lowering effects. The fermentation process in tempeh introduces beneficial microorganisms that can improve gut health by enhancing the gut microbiota. This can lead to better digestion and absorption of nutrients (Akanni and Adebo, 2024; Dimidi et al., 2019).
Nutrient Bioavailability: Fermentation increases the bioavailability of essential nutrients such as proteins, vitamins, and minerals, making tempeh a highly nutritious food option (Akanni and Adebo, 2024; Rizzo, 2024). The fermentation process enhances the bioavailability of these nutrients and produces additional metabolites, such as organic acids and antimicrobial

compounds, further increasing tempeh's nutritional value (Teoh et al., 2024). It enhances nutrient bioavailability, easing the body to absorb essential nutrients.
The diverse bioactive compounds in tempeh make it a valuable functional food with numerous health benefits, such as antihypertensive, antidiabetic, antioxidative, and antitumor, lowering the risk of cardiovascular disease and cancer, and improving bone health (Tamam et al., 2019; Surya et al., 2024). Tempeh is a nutritious food option supporting overall health and well-being, particularly for those following plant-based diets.

Bioactive compounds and health benefits of tofu
Tofu is rich in several bioactive compounds that contribute to health, primarily isoflavones such as genistein and daidzein, which are linked to reduced risks of chronic diseases like cardiovascular disease and certain cancers (Punoo et al., 2024). Additionally, bioactive peptides derived from soy proteins during processing exhibit various physiological effects, including anti-hypertensive, anti-inflammatory, and antioxidant properties (Sheneni and Momoh, 2023; Abedin et al., 2022). Some peptides, such as lunasin and soymorphins, enhance the health-promoting potential of tofu by supporting immune function and reducing inflammation (Sheneni and Momoh, 2023). Furthermore, the fermentation process of soy can yield specific peptides that further amplify these health benefits (Abedin et al. 2022). Tofu's isoflavones also regulate the intestinal microbiota, which is crucial for overall gut health (Takeuchi, 2024). Collectively, these compounds underscore tofu's status as a functional food with diverse health benefits, although further research is needed to elucidate their full action mechanism (Sheneni et al., 2023; Takeuchi, 2024).
Tofu is recognized for its health benefits, primarily attributed to several key bioactive compounds. Isoflavones, particularly genistein and daidzein, are prominent in tofu and are known for their antioxidant properties. These may reduce the risk of chronic diseases like heart disease and certain cancers (Punoo et al. 2024). Additionally, tofu is a rich source of protein, providing essential amino acids that support muscle health and overall bodily functions (Sheneni and Momoh, 2023). Moreover, phytosterols in tofu contribute to cholesterol-lowering effects, enhancing cardiovascular health (Abedin et al., 2022). The fermentation process applied in some tofu varieties can also increase the bioavailability of these compounds, further boosting their health benefits (Oh et al., 2022). However, it is important to note that the health effects can vary based on individual dietary patterns and the type of tofu consumed (Takeuchi, 2024). The combination of isoflavones, protein, and phytosterols makes tofu valuable to a health-conscious diet, as can be seen in **Table 2**.

Prospect of tempeh and tofu as contemporary alternative proteins in Indonesia
The prospects of tempeh and tofu as contemporary alternative proteins in Indonesia are promising, driven by their nutritional benefits, economic potential, and innovative product development. Both tempeh and tofu are increasingly recognized for their role in addressing protein needs in a country with an insufficient animal protein supply. Tempeh can be processed into flour, which longer shelf life and can be applied more widely. Pre-treatment and drying methods will affect the physical characteristics of tempeh flour (Herawati et al. 2024).

Nutritional and health benefits
Tempeh is rich in protein, vitamins, minerals, and bioactive compounds, enhancing its nutritional profile and making it possible to substitute animal proteins (Teoh et al., 2024). The fermentation process increases the bioavailability of nutrients and introduces beneficial metabolites, contributing to health benefits such as improving gut health and reducing cardiovascular risks (Teoh et al. 2024). The supplemental feeding *semangit* tempeh cookies to pregnant women could enhance haemoglobin and serum ferritin (Kusumawaty et al., 2023).
Tofu is a highly nutritious plant-based protein source. It is rich in essential amino acids, healthy fats, and low carbohydrates, contributing to a low glycemic index (Anjum et al., 2023). It is also rich in vitamins, minerals, and bioactive compounds, such as isoflavones and peptides, which contribute to antioxidative activities, antihypertensive, anti-cancer, anti-inflammatory, and modulatory properties (Sheneni and Momoh, 2023).

Novel product development
Innovations like Temitel, a tempeh-egg mix, demonstrate that the combination between tempeh and other ingredients to enhance flavor and appeal, potentially increase protein consumption among diverse consumer groups (Halawa et al., 2024). Research on using lotus seeds as a tempeh base highlight the potential for alternative ingredients, addressing soybean supply issues while maintaining nutritional value (Khosyiati et al., 2024).
Tofu dreg, a by-product of tofu production, is rich in protein and bioactive compounds, making it suitable for high-protein food products like *tempe gembus* and snacks (Ginting et al., 2024). This diversifies local food options and adds economic value, contributing significantly to tofu producers' income (Ginting et al., 2024).

Sustainable contributions
Tempeh production utilizes less land and water compared to animal protein sources, making it a more sustainable option (Teoh et al., 2024). Optimizing fermentation processes can extend shelf life and reduce food waste, further enhancing sustainability in food systems (Sudaryatiningsih and Pambudi, 2024).
Implementing circular economic principles can transform tofu waste into valuable products. Tofu dregs can be repurposed into flour for baking or animal feed, while tofu whey can serve as a functional food additive, enhancing nutritional profiles

(Stanojevic et al., 2023). Tofu is promising for sustainable food systems, but challenges remain in standardizing production and addressing environmental impacts associated with traditional methods (Wang et al., 2023).

Conclusions

Tempeh and tofu are essential plant-based alternative protein sources in the Indonesian diet. Both have a long history in local culinary traditions and contribute significantly to addressing the country's growing protein needs. The fermentation process in tempeh enhances nutrient bioavailability, producing bioactive compounds that offer health benefits, such as antioxidant, antihypertensive, and anticancer properties. Tofu, though unfermented, is rich in protein and bioactive peptides, providing antioxidant and anti-inflammatory effects. Beyond their high nutritional value, tempeh and tofu hold great potential for supporting food sustainability due to their lower resource requirements compared to animal-based proteins. Innovations in the processing tempeh and tofu products further enhance their capacity to meet future protein demands while boosting both economic growth and public health.

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Statement of Contributions

R.R.: conceptualization, writing an original draft, reviewing, and editing; N.K.: writing, reviewing, and editing; A.C.I.: reviewing; D.K.: writing and editing; E.R.N.H.: writing, reviewing and editing; D.A.: funding acquisition; M.M.: project administration; R.C.E.A.: editing; M. B.: editing.

Conflicts of Interest

The authors declare no conflict of interest.

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