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Fermented foods of Southeast Asia other than soybean- or seafood-based ones

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Abstract

The region of Southeast Asia encompasses a group of countries that include Indonesia, Malaysia, Thailand, Cambodia, Vietnam, Laos, Singapore, Myanmar, Brunei, and the Philippines. Such a region is the home of diverse ethnic people and culture, including richness in terms of indigenous fermented foods. Among the fermented foods in Southeast Asia, only those made from soybeans and fish (or seafoods) have been the most reviewed and described in international scientific media. In addition, the knowledge about fermented foods in Southeast Asia seems to be scattered and rarely available in international peer-reviewed scientific journals. Therefore, it appears primordial to create a comprehensive review on fermented foods from Southeast Asia as a gastronomic heritage and introduce them toward an international academic audience. This review aims to explore the diversity of fermented foods from Southeast Asian nations and discuss their characteristics in several aspects, including biochemical, microbiological, ethnic, and cultural aspects. The fermented foods discussed in this review are divided into seven categories, including: (1) fermented starch products, (2) fermented alcoholic beverages and vinegar, (3) fermented vegetable and fruit products, (4) fermented non-soybean legumes, (5) fermented dairy products, (6) fermented meat products, and (7) other fermented foods from Southeast Asia. These fermented foods have been very little reviewed and discussed compared to the soybean- and seafood-based fermented products from Southeast Asia. It is expected that this review would provide a thorough explanation regarding fermented foods from Southeast Asia, become a reliable reference for scientific studies, and ultimately promote future research in ethnic food fermentation.

Keywords Fermentation, Southeast Asia, Ethnic foods

Introduction

Food, as a human's basic necessity, has been an integral part of human civilization since ancient times. The formation and growth of a food culture occur gradually, shaped by the shared values, customs, and traditions within a community. Consequently, certain cultural cuisines are closely linked to the identity and heritage of a particular group. Over the course of history, food has evolved in tandem with human progress, fostering a sense of belonging within societies and ultimately becoming an integral element of their widely accepted culture [1]. In the present day, the consumption of ethnic foods remains a prevalent practice in numerous countries across the globe. Fermented vegetables like *sauerkraut* (Germany) and *kimchi* (Korea) have been staples for millennia [2–4]. Furthermore, these foods have become the pride and identity of the corresponding nations, as recognized by the people [5].

Food fermentation is one of the earliest food processing technologies developed during human history. Fermented foods are the product of a natural transformation process where microorganisms like bacteria, molds, and yeasts break down ingredients, often enhancing flavor and nutritional value [6]. Food fermentation in human food culture likely began unintentionally when early

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humans stored food in containers made of materials like animal hides or plant leaves [7]. Microorganisms naturally present in the environment would come into contact with the food and initiate the biochemical transformation. This process was observed in the transformation of fruits, grains, and milk into fermented food products like alcoholic beverages, bread, and yogurt. Food fermentation has been recorded in many historic documents regarding ancient civilizations. Various cultures embraced fermentation in their cuisines. The earliest recorded use of fermentation was the production of alcoholic beverages, which dates back over 7000 years ago in Mesopotamia, Egypt, and China [7]. Later, the development of leavened bread around 3000 BC in Egypt and dairy fermentation products around 2000 BC in the Middle East and India marked a significant advancement in fermentation [7]. The Industrial Revolution commencing in the eighteenth century brought significant changes in food production, including the large-scale production and commercialization of fermented foods like cheese, beer, and yogurt [7]. Today, food fermentation continues to evolve. Amidst the popularity of traditional fermented foods, there is a resurgence of interest in exploring the health benefits of consuming fermented foods [8].

Southeast Asia is a diverse and vibrant region located in the southeastern part of Asia, encompassing a group of countries and territories that share both geographical proximity and cultural richness. Geographically, Southeast Asia is situated south of mainland China, east of the Indian subcontinent, and north-west of mainland Australia which is part of Oceania. The region of Southeast Asia comprises 10 main countries (Fig. 1), including Indonesia, Malaysia, Thailand, Cambodia, Vietnam, Laos, Singapore, Myanmar (Burma), Brunei, and the Philippines [9]. These nations are united under a political and economic union established in 1967 named the Association of Southeast Asian Nations (ASEAN) [9]. As of 2022, ASEAN has 10 member states as enlisted earlier, a candidate state (East Timor or Timor-Leste), and an observer state (Papua New Guinea) [10]. From the cultural point of view, Southeast Asia is a melting pot of diverse cultures, languages, and religions. It is home to a wide range of ethnic groups, including Malays, Chinese, Indians, Thais, Khmers, and many indigenous people [11]. Such a cultural diversity is reflected in the region's languages, traditions, and foods. With regard to the latter, Southeast Asian is a home to a plethora of ethnic fermented foods that are unique compared to other fermented foods from other regions in the world, particularly due to the use of Southeast Asian indigenous natural ingredients in the production process. Among the existing fermented foods from Southeast Asia, soybean- and fish-based fermented foods seem to be the most studied and reviewed [12–15]. However, it is noteworthy that fermented foods in Southeast Asia are much more diverse since the local people use a myriad of indigenous ingredients that encompass fruits, vegetables, legumes, tubers, and even meats [16]. Unfortunately, despite the long historical background and diversity of fermented foods in Southeast Asia, these foods are relatively little studied and the information regarding these foods in scientific publications is currently rare.

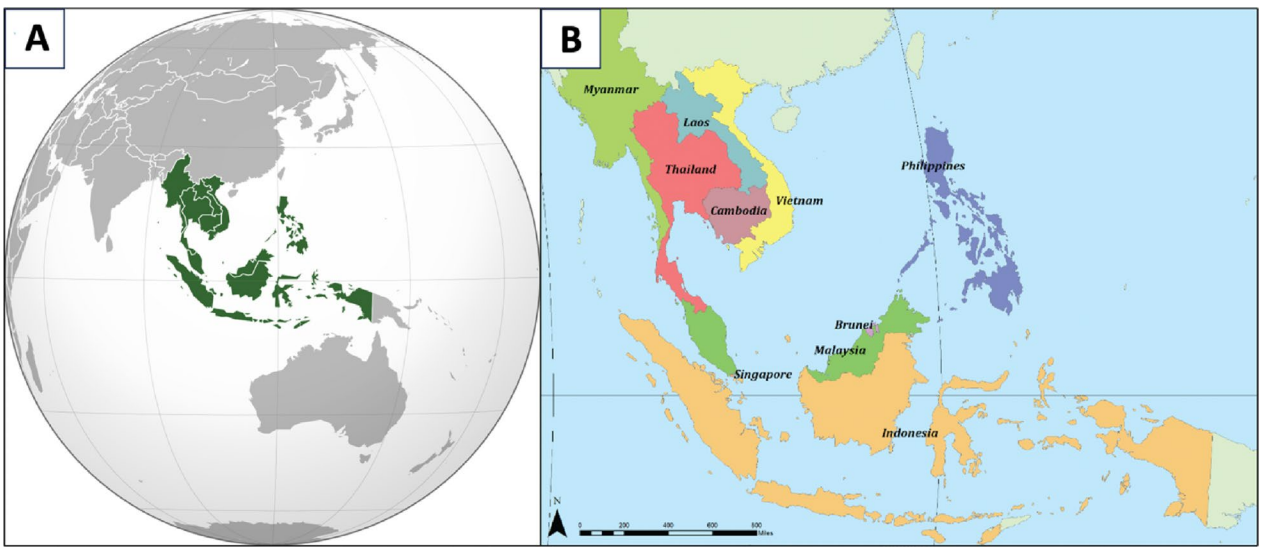

Fig. 1 **A** Location of Southeast Asia in the world map. **B** Region of Southeast Asia comprising ten countries presented in different colors

Currently, the knowledge about fermented foods in Southeast Asia seems to be scattered. Even where research on Southeast Asian fermented foods has occurred, little has been published in international peer-reviewed scientific journals since most findings are mainly reported at conferences, in reports that are not widely disseminated, or in national journals that are not written in English. Such a deplorable phenomenon would hamper research progress and not provide encouragement to undertake research in this area. Therefore, it appears primordial to create a comprehensive review on fermented foods from Southeast Asia and introduce them toward an international academic audience. This review aims to explore the diversity of fermented foods from Southeast Asian nations and discuss their characteristics in several aspects, including biochemical, microbiological, ethnic, and cultural aspects. This review focuses on indigenous fermented foods that are neither soybean-based nor fish-based since these foods have been little studied. It is expected that this review would complement previous scientific reviews on soybean- and fish-based fermented foods from Southeast Asia and ultimately, provide the readers with a thorough description and explanation of fermented foods from Southeast Asia. This review would also become a reliable reference for scientific studies and promote research in the area of food fermentation.

Methodology

The information in this review was collected from various books and scientific articles from different databases, such as Google Scholar and Scopus. In addition, several online sessions of focus group discussions were held with academicians, food scientists, and culinary experts from different countries in Southeast Asia. These discussions aimed to list the indigenous fermented foods from each Southeast Asian country and gain information about their characteristics and production processes.

Results

Food culture in Southeast Asia

Southeast Asia is a diverse region consisting of different nations, each of which possesses different and unique cultural elements. Table 1 represents the diverse demographic profile of the member countries in Southeast Asia [17]. Southeast Asia is indeed an important region in terms of population number since the region harbors Indonesia, ranked fourth among the most populous countries in the world as of 2020 with around 270 million people. Home to more than 650 million people, Southeast Asia represents a vast cultural diversity and complex ethnic structure that are intertwined in all life aspects, including in its food culture.

Food culture in Southeast Asia has been shaped according to each nation's unique characteristics. It is a captivating tapestry of flavors, techniques, and traditions that reflect the region's history, geography, and multiculturalism [18]. Regional specialty is one of the main characteristics of Southeast Asian cuisine. Different regions within Southeast Asian countries have their own specialties that are unique and have been globally famous, such as *tom yum goong* (sour and spicy prawn soup) from Thailand, *rendang* (slow-cooked beef in coconut milk and herbs) from Indonesia, *pho* (soup consisting of bone broth, rice noodles, and thinly sliced meat) from Vietnam, and *adobo* (meat stew in vinegar and soy sauce) from the Philippines [19]. Within a Southeast Asian region or country, traditional foods also vary. For instance, northern Thai cuisine differs from northeastern Thai (Isaan region) and southern Thai cuisine, and as an

Table 1 Demographic profiles of countries in Southeast Asia [17]

Country	Population (2020)	Religion(s)	Major ethnic group(s)
Brunei	460,345	Islam (81%), Christianity (7%), Buddhism (7%)	Malay (70%), Chinese (10%)
Cambodia	16,713,015	Buddhism (97%), Islam (2%)	Khmer (96%), Cham (2%), Chinese (1%)
Indonesia	270,203,917	Islam (87%), Christianity (11%)	Javanese (40%), Sundanese (16%), Malay (4%)
Laos	7,749,595	Buddhism (66%), Tai folk religion (31%)	Lao (53%), Khmu (11%), Hmong (9%), Phu Thai (3%), Tai (3%)
Malaysia	32,447,385	Islam (64%), Buddhism (19%), Christianity (9%), Hinduism (6%)	Malay (57%), Chinese (23%), indigenous groups (12%), Indian (7%)
Myanmar	57,526,449	Buddhism (88%), Christianity (6%), Islam (4%)	Bamar (68%), Shan (9%), Karen (7%), Rakhine (4%), Chinese (3%)
Singapore	5,637,000	Buddhism (31%), no religion (20%), Christianity (19%), Islam (16%), Taoism (9%), Hinduism (5%)	Chinese (74%), Malay (14%), Indian (9%)
Thailand	69,648,117	Buddhism (90%), Islam (4%), Christianity (3%)	Thai (80%), Thai Chinese (10%), Malay (7%), Khmer (3%)
Timor-Leste	1,340,513	Christianity (~ 100%)	East Timorese (~ 100%)
Vietnam	96,208,984	No religion (74%), Buddhism (15%), Christianity (9%)	Kinh Vietnamese (85%)

archipelago, Indonesian cuisine varies from one island to another [20].

In general, rice is a staple food in most Southeast Asian countries and it is consumed as many as three times a day in every meal as a cheap source of energy and protein. Southeast Asian cuisine places a strong emphasis on achieving a harmonious balance of flavors. Traditional dishes often combine the basic tastes (sweet, sour, salty, and umami) through a mixture of different ingredients. The generous use of spices and herbs is also a key aspect in Southeast Asian food culture that is renowned for its bold and vibrant flavors, including spiciness and heat. Ingredients like chili peppers, ginger, galangal, lemongrass, and basil play a prominent role in seasoning dishes [18]. Traditional cooking methods are still widely employed, such as grilling, steaming, and stir-frying. In addition, the use of clay pots, bamboo steamers, and leaves for cooking imparts unique flavors and textures to the dishes [18]. The use of bare hands while eating is still widely practiced [21], even though the use of cutlery and chopsticks is also a common adapted dietary culture.

Given the Southeast Asia's extensive coastline, seafood has become a significant natural resource and is a prominent feature in the traditional diet. Fresh and fermented seafood has widely become an integral part of Southeast Asian food culture. Pacific Ocean and Indian Ocean, along with South China Sea, Andaman Sea, Philippine Sea, and Java Sea are responsible for the abundance of seafood in Southeast Asia [14]. Some countries in Southeast Asia are parts of the most diverse and biologically complex marine ecosystem on the planet known as the Coral Triangle. Covering 5.7 million km^2, this extraordinary expanse of ocean spans across parts of Indonesia, Malaysia, the Philippines, Timor-Leste, Papua New Guinea, and the Solomon Islands [22]. In addition to seafood, freshwater fish are also an important element in Southeast Asian food culture owing to the paramount role of Mekong (Lancang) River, the world's twelfth-longest river and the third-longest in Asia with an estimated length of 4,909 km and a drainage area of 795,000 km^2 [23]. From its headwaters in China, the river runs through several countries in Southeast Asia, including Thailand, Laos, Cambodia, Myanmar, and southern Vietnam [23].

Food plays a significant role in the cultural and social fabric of Southeast Asian societies. It is often deeply intertwined with cultural and religious practices. Food is used in celebrations, rituals, and religious ceremonies, connecting people to their communities and ancestors [21]. The act of eating together and sharing food with family and friends is deeply rooted in the customs. Religion is also a determining element in the food culture of Southeast Asian countries. As the people of Southeast Asian nations embrace different religions, the food culture of each country differs from each other. Among the religions in Southeast Asia, the largest are Islam (42%) and Buddhism (38%) [24]. In countries where Islam is the predominant religion, such as Indonesia, Malaysia, and Brunei, food is *halal* (prepared according to the Sharia Islamic Law) and does not contain pork, a common ingredient found widely in other Southeast Asian countries such as Thailand, Singapore, and the Philippines. Hinduism is a minor religion in Southeast Asia, and in some areas where most people embrace Hinduism, such as Bali Island in Indonesia, beef is not commonly consumed according to the Hindu religious law [25].

The food culture in Southeast Asia is strongly shaped and influenced by other cultures and interactions with neighboring countries. Chinese, Indian, and Arab influences, among others, have left a lasting mark on the region's culinary traditions [18]. For instance, Chinese-style noodles and Indian spices like curry are prevalent in various dishes in the region. Chinese influences have given birth to *Peranakan* or *Nyonya* cuisine resulting from an acculturation between Malay and Chinese food culture mainly found in Malaysia and Indonesia [26, 27].

Food fermentation in Southeast Asia

Food fermentation is defined as a food processing technology that utilizes the growth and metabolic activity of microorganisms for the stabilization and transformation of food materials [28]. In the beginning, fermentation was primarily developed to prolong the shelf life of perishable foods. Notwithstanding, the technology has now evolved beyond food preservation into a method for creating foods with higher nutritional values and more desirable nutritional, organoleptic, and functional attributes. In the modern global food culture, fermented foods still make up a significant portion of the diet in most Asian countries [29], including the nations in Southeast Asia where food fermentation is a time-honored culinary tradition deeply ingrained in its food culture.

Historically, food fermentation has been practiced in Southeast Asia for thousands of years. Rice wine and *tapai*, a traditional fermented preparation of rice or other starchy foods found throughout Southeast Asia, were firstly discovered in prehistoric China in 7,000 BC before the migration of Proto-Malay people from Yunnan, South China to present-day Thailand, Malaysia, and Indonesia around 3,000 BC [16]. Soy sauce, a main and ubiquitous fermented soybean-based seasoning in Southeast Asian cuisine, is believed to have originated in China over 2500 years ago and spread to Southeast Asia through trade routes and migration [30]. Later, this led to the development of various regional soy sauces in Southeast Asian countries, such as *kecap manis* in Indonesia,

siu khrong muu in Thailand, and *toyo* in the Philippines. Fish sauce, often referred as the 'umami of Southeast Asia,' has a long and history dating back to 300 BC, during which the early civilizations in the region, such as the Khmer Empire in present-day Cambodia and the Funan Kingdom in the Mekong Delta, were known to produce and use fish sauce as a condiment in local foods [30]. Fermented shrimp paste, a seasoning agent commonly used in many Southeast Asian foods, has existed in Java, Indonesia, as early as the sixth century and later spread throughout Southeast Asia through trades [31]. Some variations of fermented shrimp paste in other Southeast Asian countries include *terasi* in Indonesia, *kapi* in Thailand, *belacan* in Malaysia, *mam tom* in Vietnam, and *bagoong alamang* in the Philippines [32]. It is noteworthy that rice, soybean, and seafood have been the most prominent raw materials for fermented foods in Southeast Asia and the local knowledge regarding the fermentation of these ingredients was the earliest food technology knowledge in the region that ultimately led to the fermentation of other natural sources.

The culture of food fermentation in Southeast Asia, similar to most other parts of the world, was born from the urge to preserve food and maintain food security. Indeed, food fermentation was a particularly important food processing technology developed in Southeast Asia as a region with a tropical climate where food spoilage was a constant concern. Techniques and practices of preserving plants (such as rice and soybeans) and seafoods were developed as a strategy to balance the fluctuation in food availability in the area during the stage of monsoonal circulation [18].

Compared to the other parts of the world, food fermentation in Southeast Asia exhibits several unique characteristics. Food fermentation in Asia, including Southeast Asia, is noted for its much wider utilization of fungi (molds and yeasts) than is the case in Western countries [18]. *Tempeh*, a soybean cake made via fungal fermentation using *Rhizopus* sp., is an example of unique fermented food from Indonesia that offers interesting nutritional values and health benefits [33]. Southeast Asian fermented foods also create a diversity of products from indigenous natural resources that differ from other countries. The abundance of rice and seafood has played a great role in fermentation since an array of fermented food products are derived from these ingredients. Indeed, other ingredients that are commonly used in Southeast Asian fermented foods are soybeans, cassava, durian, coconut water, as well as from various waste products of tofu, tapioca, peanut oil, and coconut industries [18]. Southeast Asia also preserves its rich heritage of unique traditional fermentation techniques. For instance, the process of 'buried fermentation' is used in Indonesia to produce *tapai* from cassava or glutinous rice [34]. Plant leaves are often used to wrap in the traditional production of tempeh and fermented shrimp paste [35]. Additionally, bamboo containers are often used to ferment *dadih*, a fermented buffalo milk from Minangkabau (West Sumatra), Indonesia [36].

This review discusses the fermented foods from Southeast Asia that are categorized into several types: (1) fermented starch products, (2) fermented alcoholic beverages and vinegar, (3) fermented vegetable and fruit products, (4) fermented non-soybean legumes, (5) fermented dairy products, (6) fermented meat products, and (7) other fermented foods from Southeast Asia. These fermented foods have been very little reviewed and discussed compared to the soybean- and seafood-based fermented products from Southeast Asia. Table 2 recapitulates the indigenous fermented food products in Southeast Asia that are discussed in this review.

Fermented starch products in Southeast Asia

Starch is the most common carbohydrate in the human diet and is present in many staple foods worldwide. The major sources of starch include cereals (rice, wheat, and maize) and root vegetables (potatoes, sweet potatoes, and cassava). In Southeast Asia, rice (*Oryza sativa*) is the main staple food, while other sources of starch are also commonly consumed. Some sources of starch that are widely and uniquely consumed in Southeast Asia are glutinous rice, cassava (*Manihot esculenta*), sago (*Cycas revoluta*), maize (*Zea mays*), and sweet potatoes (*Ipomoea batatas*) [16].

Chemically, starch is a polymeric carbohydrate consisting of glucose units joined by glycosidic bonds [37]. The fermentation of starchy ingredients begins by amylolytic activity that degrades starch into molecules of glucose [38]. This process is mainly done using amylolytic molds producing amylases usually present in the form of a starter culture. The formation of glucose molecules results in a final product with sweet taste. In some cases, fermented starch is further processed into alcoholic beverages using yeasts that metabolize glucose into alcohol and carbon dioxide under anaerobic conditions [38].

Tapai (also known as *tapay* or *tapé*) is a traditional fermented preparation of rice or other starchy foods that has a sweet and sour taste with the presence of alcohol. The term refers to both the paste and the alcoholic beverage derived from it. *Tapai* is traditionally made from white rice, glutinous rice, or cassava (Fig. 2A, B). The fermentation of *tapai* is performed by a variety of molds (*Aspergillus oryzae*, *Rhizopus oryzae*, *Amylomyces rouxii*, *Mucor* sp.), yeasts (*Saccharomyces cerevisiae*, *Saccharomyces fibuliger*, *Endomycopsis burtonii*), along with bacteria [39]. *Tapai* is

Table 2 List of fermented food products of Southeast Asia other than soybean- and seafood-based ones

Fermented food	Substrate	Main microorganisms	Country	Culinary application	Variation
Fermented starch foods					
Angkak (red yeast rice)	Rice	Mold (*Monascus purpurea*)	Philippines	Food colorant (red)	–
Khanom chin (fermented rice noodles)	Rice	Lactic acid bacteria	Thailand	Staple, eaten with soups and curries	*Bun* (Vietnam), *num banhchok* (Cambodia), *mont di* (Myanmar)
Tapai	Glutinous rice	Molds and yeasts	All Southeast Asian countries	Dessert, rice cakes, dried cakes, rice wine	*Tapai ketan* (Indonesia), *tapai pulut* (Brunei and Malaysia), *binuburang basi* (Philippines), *khao mak* (Thailand)
Tapai	Cassava tuber	Molds and yeasts	All Southeast Asian countries	Dessert, alcoholic beverages	*Peuyeum* or *tapai singkong* (Indonesia), *tapai ubi kayu* (Malaysia), *binuburang kamoteng kahoy* (Philippines)
Fermented alcoholic beverages and vinegar					
Air tapai (*tapai* water)	Cassava tuber	Molds and yeasts	Indonesia	Alcoholic beverage	*Ruou can* (Vietnam)
Arak, *tuak*	Plant sap	Yeasts	Indonesia	Alcoholic beverage	–
Basi	Sugar cane	Yeasts	Philippines	Alcoholic beverage	*Ciu* (Indonesia)
Rice wine	Rice, glutinous rice	Molds and yeasts	All Southeast Asian countries	Alcoholic beverage (usually distilled or fortified), used in cuisine	*Brem* (Indonesia), *satoh* (Thailand), *tapuy* (Philippines), *ruou de* (Vietnam), *lao-Lao* (Laos), *sra peang* (Cambodia)
Vinegar	Rice wine	Acetic acid bacteria	All Southeast Asian countries	Food flavoring agent in cuisine	*Cuka* (Indonesia and Malaysia), *suka* (Philippines)
Fermented fruit and vegetable products					
Budu pakis	Fern fronds	Lactic acid bacteria	Brunei	Consumed as a side dish	–
Fermented mustard greens	Mustard greens	Lactic acid bacteria	All Southeast Asian countries	Used in cuisine or as a condiment	*Phak kat dong* (Thailand), *som pak gaat* (Laos), *jrouk spey* (Cambodia), *dua chua* (Vietnam), *burong mustasa* (Philippines), *sayur asin* (Indonesia)
Nata de coco	Coconut water	Acetic acid bacteria	Philippines	Dessert	–
Nata de piña	Pineapple extract	Acetic acid bacteria	Philippines	Dessert	–
Tempoyak	Durian flesh	Lactic acid bacteria	Indonesia, Malaysia, Brunei	Used in cuisine and chili paste	–
Fermented non-soybean products					
Non-soybean tempeh	Different kinds of legumes	Molds (*Rhizopus oligosporus* and *Rhizopus oryzae*)	Indonesia	Used in cuisine, often used as a meat substitute by vegetarians and vegans	–
Pon ye gyi	Horse gram beans	Lactic acid bacteria	Myanmar	Used in cuisine	–
Fermented dairy products					
Dadih	Buffalo milk	Lactic acid bacteria	Indonesia	Yogurt-like drink, used in cuisine	–

Table 2 (continued)

Fermented food	Substrate	Main microorganisms	Country	Culinary application	Variation
Dangke cheese	Buffalo milk	Lactic acid bacteria	Indonesia	Used in cuisine	*Dali ni horbo* cheese (Indonesia), *kesong puti* (Philippines)
Tairu	Cow milk	Lactic acid bacteria	Malaysia	Yogurt-like drink, used in cuisine	–
Fermented meat products					
Bekamal	Beef, goat, or lamb meat	Lactic acid bacteria	Indonesia	Eaten with rice in a bamboo container as *bekamal* rice (*nasi bekamal*)	–
Belutak	Beef, cow intestine	Lactic acid bacteria	Brunei	Used in cuisine, usually fried with chilies and onions	–
Naem	Pork	Lactic acid bacteria	Thailand	Eaten raw or cooked as part of a main meal	*Nem chua* (Vietnam), *som moo* (Laos)
Sai krok Isaan	Pork, pig intestine	Lactic acid bacteria	Thailand	Fried and eaten as a snack or part of a main meal	–
Urutan	Pork, pig intestine	Lactic acid bacteria	Indonesia	Fried and eaten as a snack or part of a main meal	–
Other fermented food products					
Civet coffee (*kopi luwak*)	Fermented coffee grains extracted from the feces of Asian palm civet	Microflora in the digestive tube of Asian palm civet, in addition to the digestive enzymes	Indonesia	Brewed as a coffee drink	–
Dage or *oncom*	Edible press cake (waste from oil industries)	Molds (*Mucor* sp., *Rhizopus oryzae*, *Neurospora crassa*, etc.)	Indonesia	Used in cuisine	Black *oncom* made from peanut press cake, red *oncom*, made from soybean press cake, *bongkrek* made from coconut press cake (all from Indonesia)
Miang	Tea leaves	Lactic acid bacteria	Thailand	Chewed, used in cuisine	*Lahpet* (Myanmar)
Salted duck egg	Duck egg	Lactic acid bacteria	All Southeast Asian countries	Eaten raw, used in cuisine	*Telur asin* (Indonesia), *itlog na maalat* (Philippines)
Sriracha sauce	Jalapeño pepper	Lactic acid bacteria	Thailand	Used in cuisine as a condiment	–

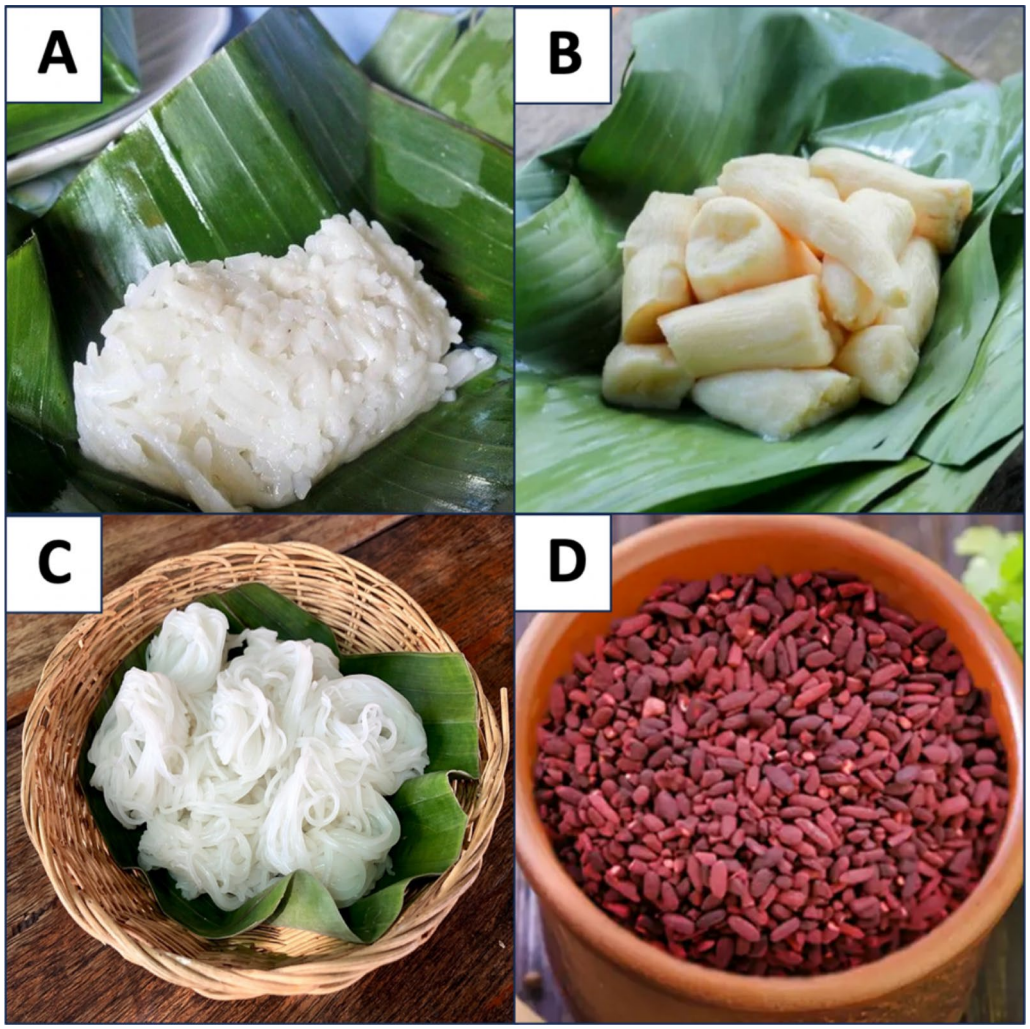

Fig. 2 Fermented food products in Southeast Asia that are derived from starch: **A** *tapai* made from cooked glutinous rice, **B** *tapai* made from cassava tuber, **C** fermented rice noodles known as *khanom* chin in Thailand, and **D** red yeast rice known as *angkak* in the Philippines

made by inoculating a pre-cooked starchy raw material with a starter culture containing microorganisms (*ragi* in Indonesia and Malaysia, *look paeng* in Thailand, or *bubod* in the Philippines) and followed by anaerobic fermentation in a closed container (traditionally in an earthenware jar) for 1–2 days [39]. Depending on the fermentation time and various processes, *tapai* may result in several end products. These include fermented paste used for rice cakes (Filipino *galapong*), dried fermented cakes (Indonesian *brem* cakes), fermented rice with shrimp (Filipino *balao-balao*), dessert (Thai *khao mak* and Vietnamese *com ruou*), or various rice wines (Filipino *tapuy* and Indonesian *brem* wine) [40]. In West Java, Indonesia, *tapai* made from cassava tuber is also called *peuyeum* [34]. It is usually consumed as it is, battered and deep fried, or used as an ingredient in desserts. In Malaysia, *tapai* made from rice is called *tapai pulut* while the one made from cassava is called *tapai ubi* [41].

Khanom chin or *kanomjeen* (Fig. 2C) are traditional Thai fermented rice noodles. The traditional process of making *khanom chin* embraces three fermentation stages [42]. The rice is washed, soaked, and drained, and the moist grains are stored in bags for 2–3 days to allow the first fermentation to occur. Salt is then added to the softened rice grains, and the slurry undergoes the second fermentation overnight. The released water is removed, and the third fermentation takes place for 2–3 days. The fermented rice starch is partially gelatinized, kneaded, and extruded to form noodles in boiling water. Fermented rice noodles are called *khanom sen* in northern Thailand, *kao pun* in northeastern Thailand, and *nom chin* or *lasa* in southern provinces [42]. Lactic acid bacteria are the main microorganisms in the fermentation

of *khanom chin*, such as *Lactobacillus*, *Leuconostoc*, *Lactococcus*, *Enterococcus*, *Pediococcus*, and *Streptococcus* [43]. Yeasts are also commonly present in minor amount [43]. *Khanom chin* is mainly served with stock, such as coconut stock, curry sauce, or chili sauce. It is eaten with fresh vegetables and pickles as condiments. Some popular dishes using *khanom chin* are *khanom chin nam ya* (served with a hot and spicy fish-based sauce), *khanom chin nam prik* (served with a sweet peanut-based sauce), and *khanom chin nam ngiao* (a northern Thai speciality, served with sauce containing pork blood) [44]. Similar noodles are also found in other Southeast Asian cuisines, such as *bun* in Vietnam, *num banhchok* in Cambodia, and *mont di* in Myanmar [44].

In some Southeast Asian countries, fermented rice is further processed to make fermented rice flour. The final process of flour preparation consists in drying and grinding fermented rice to produce flour. In Vietnam, fermented rice flour is used to make rice crepe or rice sheet that is used as the wrap of *banh cuon* (steamed rice rolls filled with pork and mushrooms) [45].

Another traditional practice of rice fermentation in Southeast Asia is the preparation of red yeast rice (*angkak* in the Philippines, Fig. 2D). It is a bright reddish fermented rice grains which acquire their color from being cultivated with the mold *Monascus purpureus* [46]. In the Philippines, red yeast rice is traditionally used as a food coloring agent in many traditional foods, such as *bagoong alamang* (fermented shrimp paste), *burong isda* (fermented rice and fish), and *balao-balao* (fermented rice and shrimp) [47].

Fermented alcoholic beverages and vinegar in Southeast Asia

Fermented alcoholic beverages have been culturally and socially used by humankind for consumption, entertainment, customary practices, and religious purposes for thousands of years [21]. Alcoholic beverages have a strong ritualistic importance among Southeast Asians whose social activities require the provision and consumption of appreciable quantities of alcohol, particularly in non-Muslim countries. The production of alcoholic beverages through fermentation generally accompanies or follows the fermentation of starchy foods as previously discussed. For example, along with *tapai* (fermented rice or cassava), a liquid containing alcohol is also formed and extracted as an alcoholic beverage.

The production of fermented alcoholic beverages requires yeasts as the main microorganisms that metabolize simple sugars such as glucose to alcohol and carbon dioxide [48]. The most well-studied yeast species for producing fermented alcoholic beverages is *Saccharomyces cerevisiae*. The raw materials for fermented alcoholic beverages should be natural resources rich in simple sugars for a direct fermentation by yeasts. Starchy materials, such as rice and cassava can also be used as raw materials following amylolytic digestion that allows the bioformation of glucose molecules from starch. This process is often done by microorganisms present in the starter culture incorporated in the substrate, particularly molds producing amylases. Following the fermentation, the alcohol content in the final product is in general 7–12% since too high level of alcohol inhibits the growth of yeasts [49]. An additional step is required if the final product is expected to contain a higher concentration of alcohol. This step consists in evaporating alcohol and volatile flavor components from the final fermented beverage using heat prior to condensation in a cooler compartment. Distillation may result in an alcoholic beverage with an alcohol content as high as 70% [49]. From the appearance, the final products of alcoholic fermentation are generally turbid with some sediments while distilled alcoholic beverages are clear and transparent.

Different types of fermented alcoholic beverages are present in Southeast Asia. The fermentation of rice or cassava into *tapai* can be continued to produce alcoholic beverages such as *air tapai* (*tapai* water) in Indonesia and *tapuy* in the Philippines (Fig. 3A, B) [50]. In Thailand and Vietnam, rice-based alcoholic beverages are also popular. *Satoh* or *krachae* from Thailand is a traditional, non-distilled, fermented alcoholic beverage prepared from a local Thai rice variety [50]. In Vietnam, the similar product is called *ruou de* (made from rice), *ruou nep* (made from glutinous rice) or *ruou nep than* (made from purple glutinous rice) [50]. In Vietnam, the vast majority of alcoholic beverages produced from rice are either distilled or fortified with added alcohol [48]. Fermented alcoholic beverages made from other ingredients besides rice also exist in Vietnam, particularly among the ethnic minority Thuong people living in the mountainous districts of the Vietnamese central highlands, such as *ruou can* made from fermented maize or cassava [48].

In addition to starchy raw materials, some natural resources rich in sugar are also used in the production of fermented alcoholic beverages in Southeast Asia. *Ciu* from Indonesia and *basi* from the Philippines are examples of fermented alcoholic beverages made from cane sugar [21]. *Arak* and *tuak* are traditional fermented alcoholic beverages made from plant sap from Bali, Indonesia [51]. *Arak* is made by fermenting coconut sap followed by distillation while *tuak* is made from the sap of sugar palm (*Arenga pinnata*) [51].

In Southeast Asia, the ethnic utilization of fermented alcoholic beverages goes further than merely consumption for social activities and entertainment. In many cases, the consumption of fermented alcoholic

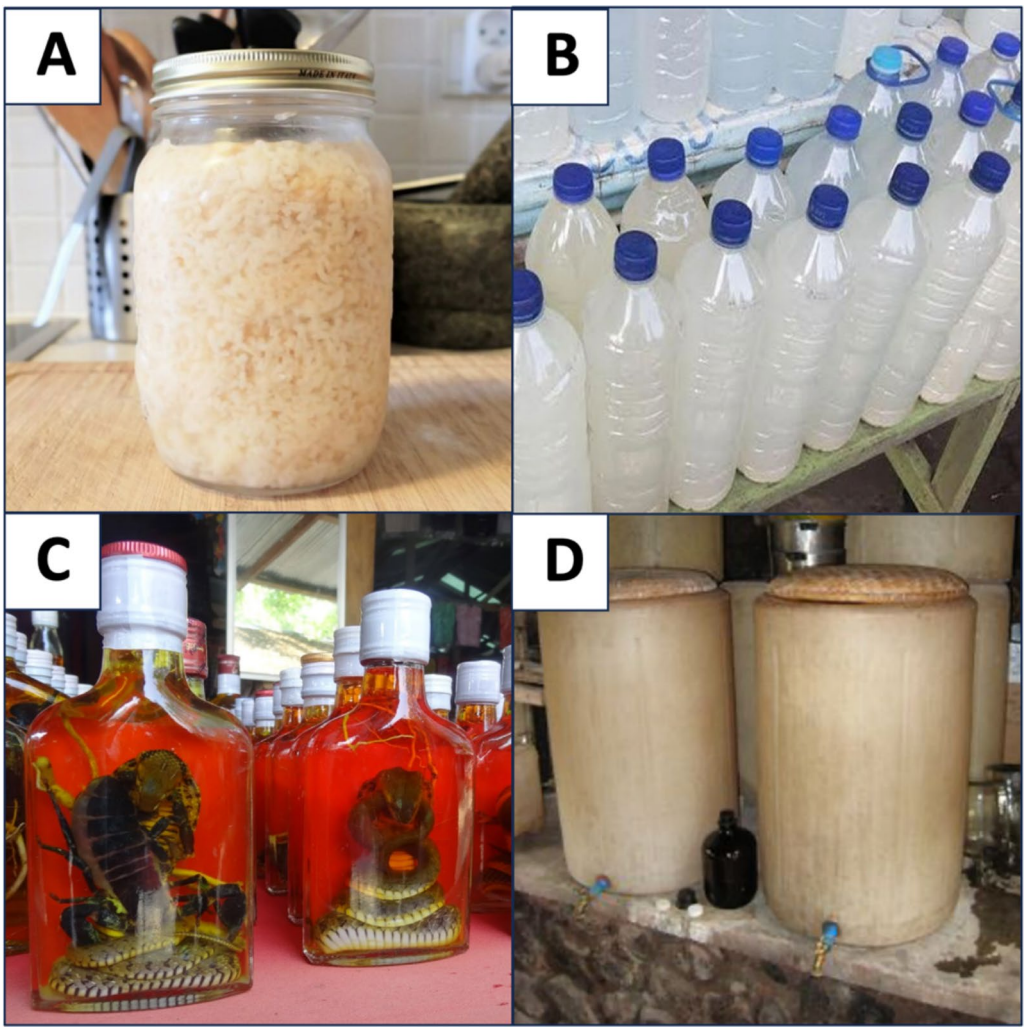

Fig. 3 Fermented alcoholic beverages and vinegar in Southeast Asia: **A** anaerobic fermentation of rice with amylolytic starter culture resulting in *tapai* and liquid containing alcohol, **B** extracted liquid alcohol from *tapai* commercialized as alcoholic beverages in the market, **C** fermented alcoholic beverages from Laos infused with animals (such as scorpions and cobras), **D** further aerobic fermentation of alcoholic beverages in wooden containers to make vinegar

beverages is associated with religious activities and health. In Bali, Indonesia, liquid *brem* made from fermented rice are often used as an offering in religious Hindu rituals or ceremonies [51]. The ceremonial drinking of *sra peang* (a rice-based fermented alcoholic beverage) in Cambodia is a sign of alliance closely linked with animal sacrifices [52]. *Ciu*, indigenous to Java island, has an alcohol content as high as 70% as is consumed by the locals as an ingredient in traditional herbal medicine known as *jamu* [53]. In Laos, rice liquor (*lao-Lao*) is fermented and infused with honey, ginseng roots, or even animals such as cobras and scorpions (Fig. 3C). The practice is linked to the local belief with regard to improving health and increasing stamina according to the traditional medicine [54].

Biochemically, alcoholic beverages can be further fermented to make vinegar. Such a process requires oxygen and acetic acid-forming bacteria, generally *Acetobacter* sp. transforming alcohol into acetic acid and water [55]. In Southeast Asia, vinegar is widely used to pickle vegetables, make sauces, and provide acidity in various dishes. In the Philippines, vinegar (*suka* or *sukang* in Tagalog, Fig. 3D) is particularly an essential ingredient in the Filipino kitchen. There are several types of vinegar in the Philippines based on their raw ingredients: *sukang nipa* made from nipa palm (*Nypa fruticans*), *sukang tuba* made from coconut sap, *sukang kaong* or *sukang irok* made from sugar palm (*Arenga pinnata*), *sukang maasim* made from sugar cane syrup, and *sukang Iloco* made from further fermentation of

sugar cane wine known as *basi* as previously discussed [56].

Fermented fruit and vegetable products in Southeast Asia

Fruits and vegetables are widely in every part of the world and eaten by almost everyone, including those who eat meat, eggs, and fish. In general, fruits and vegetables are easily perishable and grow seasonally. Therefore, fermentation has been opted in the past for prolonging the shelf life of fruits and vegetables as well as ensuring their availability throughout the year despite the season. Fermenting fruits and vegetables is widely practiced in my countries in the world. The most extensively studied fermented fruit and vegetable products in the world are fermented cabbage dishes known as *sauerkraut* from Germany and *kimchi* from Korea [2–4]. In Southeast Asia, vegetables are abundant and mostly consumed fresh or cooked. Fruits are generally eaten fresh or minimally processed prior to consumption.

Fruits and vegetables are sources of cellulose, a polysaccharide composed of glucose molecules, thus making them a perfect substrate for fermentation. Cellulose is digested into glucose molecules by cellulases present naturally in plants or by cellulolytic molds. In addition, fruits are also high in simple sugars that are readily fermented. Fermentation of fruits and vegetables is mostly dominated by lactic acid bacteria, particularly *Lactobacillus* and *Pediococcus*, followed by *Leuconostoc*, *Weissella*, *Tetragenococcus*, and *Lactococcus* [57]. In general, the traditional practice includes fermenting fruits and vegetables spontaneously, meaning that there is no specific culture starter added to the ingredients to begin the fermentation process. The preparation steps for fermenting fruits and vegetables consist in cleaning, cutting (if necessary), salting, and preserving in a closed container [58]. Salting is a crucial step in the preparation of fermentation since the addition of salt decreases the water activity of fruits and vegetables, thus preventing the growth of spoiling microorganisms. Wilted vegetables are rubbed or squeezed with up to 5% salt. Lactic acid bacteria can then grow and begin the fermentation since they are tolerant toward acid and salt. In some cases, sources of starch such as gelatinized paste made from rice flour or leftover liquid from washing rice are added to provide fermentable carbohydrates to ensure the production of sufficient acid during fermentation.

Fermented mustard greens (Fig. 4A) are present in many Southeast Asian countries. They are believed to originate from southern and western China, where they are popularly known as *suan cai* [59]. Fermented mustard greens are known under different names in Southeast Asian countries, including *phak kat dong* in Thailand, *som pak gaat* in Laos, *jrouk spey* in Cambodia, *dua chua* in Vietnam, *burong mustasa* in the Philippines, and *sayur asin* in Indonesia [63]. In Thailand, fermented mustard greens are incorporated into traditional Thai cuisine as an ingredient in Thai salad or as a condiment such as with khao soi, a northern Thai-style curry-noodles soup. In Vietnam, fermented mustard greens are used as a side relish or in dishes such as *thit kho du acai* (braised pork and pickled mustard), *canh cai chua* (sour mustard soup), and *com rang dura bo* (fried rice with beef and pickles) [64].

In Brunei, fern or *pakis* (*Diplazium esculentum*), an edible terrestrial fern found growing wild on the banks of streams and on wet ground in open places in the lowlands, is a popular vegetable sold in local markets and supermarkets. The curled tips and young, tender upper parts of the leaves or fronds are stripped off the stalk and generally cooked or eaten raw in salads. *Budu pakis* (Fig. 4B) is fermented fern fronds made through salting and fermentation in a closed vessel [57]. It is generally served uncooked and consumed with meals as a side dish. Unfortunately, not many people are familiar with *budu pakis* today, although it is well known among the Bruneian older generation, in particular villagers and farmers [57].

Tempoyak (Fig. 4C) is fermented durian (*Durio zibethinus*) fruit pulp and is characterized by a strong durian smell and sour taste [65]. *Tempoyak* is popular in Brunei, Malaysia, and Indonesia, particularly in southern Sumatra. In contrast to durian fruit that is consumed fresh, *tempoyak* is usually used in traditional cooking of fish and vegetable dishes [26] or as a secondary ingredient in traditional chili paste *(sambal)* [66]. Traditionally, *tempoyak* is made by mixing durian fruit pulp with salt (2–15%) prior to fermentation in an enclosed jar for 7 days at room temperature [67]. The fermentation is dominated by lactic acid bacteria, mainly *Lactobacillus plantarum*, *Lactobacillus coryneformis*, *Lactobacillus casei*, and *Pediococcus acidilactici*, besides two new species firstly identified in *tempoyak*: *Lactobacillus durianis* and *Leuconostoc durionis* [68].

In the Philippines, coconut gel *(nata de coco)* and pineapple gel *(nata de piña)* are chewy, translucent, jelly-like food produced by the fermentation of coconut water and pineapple extract, respectively (Fig. 4D). They are mainly sweetened as candies and desserts, as well as accompanying a variety of foods, including ice cream, drinks, puddings, and fruit cocktails [69]. The microbiological process during the fermentation of *nata de coco* and *nata de piña* consists in forming microbial cellulose from simple sugars through the anabolic activity of *Komagataeibacter xylinus* in the presence of oxygen [70]. Therefore, *nata de coco* and *nata de piña* are good sources of fiber. Commercially, *nata de coco* and *nata de piña* are

Fig. 4 Fermented food products in Southeast Asia that are derived from vegetables and fruits: **A** fermented mustard greens widely consumed in many Southeast Asian countries, **B** fermented fern fronds known as *budu pakis* from Brunei, **C** fermented durian fruit paste known as *tempoyak* in Indonesia and Malaysia, and **D** coconut gel made from coconut water known as *nata de coco* from the Philippines

primarily produced by incorporating bacterial cultures into coconut water or pineapple extract as substrate in a wide and shallow container to maximize the contact with air since the fermentation should be done aerobically. The initial amount of sugars in the substrate is a crucial factor for fermentation since the bacteria require these sugars to form cellulose. The bacteria will grow and form a cellulose layer on the surface of the substrate. Acetic acid is also formed as a by-product resulting from microbial metabolism. The cellulose layer is then isolated, cut into small cubes, washed to remove acetic acid, cooked, and packed [71].

It is noteworthy that in addition to fermenting fruits and vegetables, people in Southeast Asia also practice pickling, a processing technology that differs from fermentation but is often mistakenly considered the same as fermentation. The products of pickling are commonly known as pickles (Fig. 5). While both are known methods of food preservation, there are some key differences between fermentation and pickling [59]. Fermentation of vegetables relies on the action of beneficial microorganisms, primarily lactic acid bacteria. In fermentation, vegetables or other foods are salted or submerged in a brine over an extended period at room temperature or in a controlled environment to allow the growth of microorganisms that will in turn digest the present nutrients and develop a plethora of molecules supporting the organoleptic properties of the fermented foods. Fermented foods are often rich in probiotics, which are beneficial microorganisms that can provide various health benefits

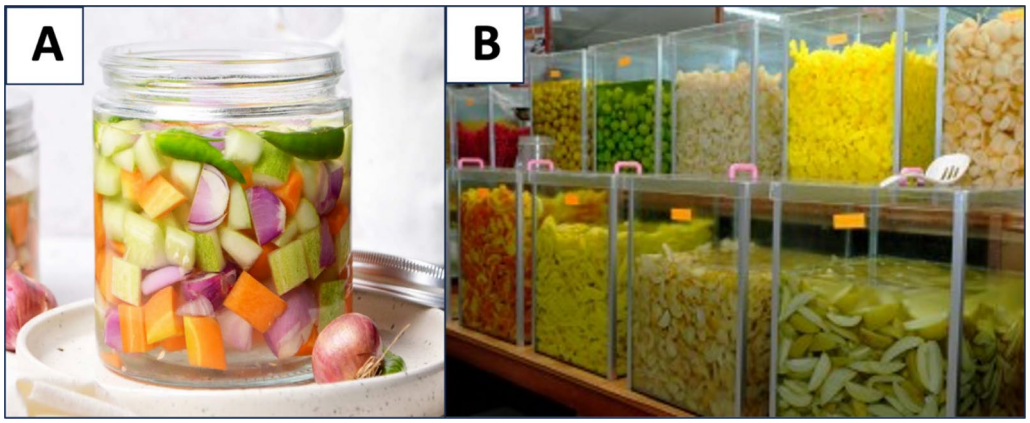

Fig. 5 Pickled vegetables and fruits in Southeast Asia: **A** *acar* from Indonesia and **B** *jeruk* from Malaysia. These foods are made by pickling, a preservation method that consists in immersing cut vegetables and fruits in an acidic solution containing salt, sugar, and vinegar. Such a method is to be differentiated with fermentation

toward human [60]. In contrast, pickling involves preserving food by immersing it in brine solution that is typically acidic, often with salt, vinegar, and sometimes sugar. The high acidity of pickling solution inhibits the growth of most microorganisms and therefore, the amount of microorganisms present in pickles is very little compared to in fermented foods [61]. Pickled foods generally have a sharp and acidic taste due to the vinegar used in the pickling solution. Different concentration and pressure between vegetables/fruits and the pickling solution creates a diffusion of solutes from the solution to the vegetable/fruit matrix and water release from vegetable/fruit matrix to the solution. Thus, pickled foods acquire its organoleptic from the pickling solution, not from microbial activity. In addition, many pickled products are pasteurized or heat-processed to kill off bacteria, including probiotics. In these cases, the preservation by pickling relies more on the acidic environment rather than microbial activity. Some examples of pickled foods in Southeast Asia are pickled assortment of fruits and vegetables (*acar* and *asinan* from Indonesia and *jeruk* from Malaysia), pickled shallots (*dua hanh*) from Vietnam, and pickled mango (*burong mangga* from the Philippines and *mamuang dong* from Thailand) [62]. *Mohnyin tjin* from Myanmar is a popular pickled dish of various vegetables preserved in rice wine and various seasonings [62]. In Southeast Asia, pickles are usually consumed as condiments for many traditional dishes [62].

Fermented non-soybean legume products in Southeast Asia

Among the legumes, soybeans are the most widely exploited in terms of fermentation. Despite soybeans not being produced in Southeast Asia (most are imported from the USA, Brazil, or China), a myriad of soybean-based fermented foods are present and consumed in Southeast Asian countries, such as tempeh and *kecap manis* (sweet soy sauce) from Indonesia, *thua nao* from Thailand, *sieng* from Laos and Cambodia, and *pepok* from Myanmar [72]. In particular, soy sauce and soybean paste are present and widely consumed in all Asian countries under their local names with processing methods that are similar to each other but also integrates local knowledge and taste. It is noteworthy that consuming soybean-based fermented foods is an ancient practice for the people in Southeast Asia. As many as 90% fermented legumes in the world are soybean-based, and the rest are non-soybean fermented foods that are mostly consumed in Africa [40]. Non-soybean legumes are abundant in Southeast Asia, but they are mainly consumed as snacks following roasting, not as fermented foods.

In general, legumes are high-protein plant foods in the human dietary system. Legumes contain essential amino acids with leucine, lysine, and valine as the generally predominant ones. Methionine is often found in less amount, thus making it the limiting amino acid in legumes. For this reason, combining legumes with cereals (that are rich in methionine but poor in lysine) is recommended to ensure the completeness of their essential amino acid profile. Such a strategy is known as protein complementation, which is compatible with the Southeast Asian food culture of consuming rice as staple food with legumes as a source of protein [73]. Other legumes are rich in carbohydrates (such as mungbeans and kidney beans) and fat (such as peanuts). Therefore, the microorganisms involved in the fermentation of legumes are generally molds with mainly proteolytic activity in addition to amylolytic and lipolytic activities. In some cases, bacteria may continue the fermentation process to form other metabolites. The fermentation of legumes results in

a higher digestibility and bioavailability of nutrients since fungal activity breaks down protein, carbohydrates, and fat into amino acids, simple sugars, and fatty acids that are more readily absorbed in human digestive system. In addition, fermenting legumes also degrades several anti-nutritional factors naturally present in legumes, such as lectins, tannins, saponins, and protease inhibitors [74]. Fermented legumes are characterized by their savory taste since the fermentation often leads to the liberation of free amino acids responsible for umami taste, such as glutamic acid [74]. Legumes also contain oligosaccharides that are indigestible by human digestive enzymes and may cause flatulence [74]. Fermentation process can degrade these oligosaccharides into simple sugars that can further be absorbed in the human digestive system.

To ensure microbial activity in the fermentation of legumes, legumes as the main raw materials should be prepared prior to incorporating culture starter. Firstly, the seed coat or hull, the outmost cover of seed that protects the seed, should be removed to allow fermenting microorganism to access the nutrients present in the embryo. Then, the legumes should be cooked to soften the seeds since otherwise, the fermenting microorganisms would not be able to penetrate into the inner part of the legumes. In several cases, the cooked legumes are crushed to form a paste to increase surface area and facilitate the access to the present nutrients for the microorganisms. In fungal fermentation, such as in the case of tempeh, the cooked legumes are soaked in water for several days to allow the growth of lactic acid bacteria that will in turn increase the acidity (decrease the pH) of the legumes to facilitate the growth of molds that prefer an acidic environment. To speed up the production process, vinegar is often added to the cooked legumes to provide acidity instead of soaking them for several days [75]. The fermentation of legumes proceeds under either aerobic or anaerobic conditions, depending on the characteristics of the final products expected.

Tempeh (Fig. 6A) is originally a traditional Indonesian food made from fermented soybeans. It is made by culturing molds (*Rhizopus oligosporus* or *Rhizopus oryzae*) that bind soybeans into a cake form [33]. It is a popular cheap source of protein in Indonesia and is highly praised among vegetarians and vegans at global level [76]. Originally, tempeh is only made from soybeans. However, in Indonesia, soybeans are mostly imported from America or China since the national production cannot fulfil the people's needs for soybeans. Therefore, many food and economy experts consider that Indonesia's high dependence on soybean consumption might not be a sustainable option for the sake of the national food sovereignty [77]. In order to diversify the utilization of non-soybean legumes, tempeh has been suggested to be made from non-soybean legumes available in Indonesia (Fig. 6B, C), such as mungbeans, peanuts, kidney beans, black-eyed beans, winged beans, and *lamtoro* (*Leucaena leucocephala*) [33, 78]. These legumes grow in Indonesia and have comparable nutritional profile with soybeans, particularly as a source of protein [33]. In some areas in Indonesia, substituting soybeans with other legumes partially or even integrally is a common practice to diversify foods. The fermentation of tempeh is carried out under aerobic conditions since *Rhizopus* sp. is an obligate aerobic mold. Traditionally, the legumes are packed in banana leaves and fermented for 2–3 days at room temperature [33].

Pon ye gyi (Fig. 6D) is a traditionally fermented bean paste from Myanmar that is commonly used as a condiment or marinade in Burmese cuisine, especially in pork and fish dishes. It is traditionally made from horse gram *(Vigna mungo)* beans originating from South Asia [79]. To prepare *pon ye gyi*, horse gram beans are boiled, pounded with salt, and fermented for about 12 h into a product similar to soy sauce, producing a viscous paste with a reddish brown color [79].

Fermented dairy products and cheese in Southeast Asia

Unlike in western countries, drinking animal milk is not a common food practice in Southeast Asia [21]. Therefore, there are only few available information regarding traditional fermented dairy products and cheese in Southeast Asian countries. Some modern people in Southeast Asia consume commercial yogurt and cheese on regular basis, but very few of them consume traditional fermented dairy products. It seems that making and consuming fermented milk and cheese is regarded to be a traditional custom of certain ethnic groups of people in certain areas.

Yogurt is an example of fermented dairy product. Yogurt is produced by bacterial fermentation of milk using lactic acid bacteria that transform lactose in the milk into lactic acid. This latter acts on milk protein to give yogurt its texture and characteristic tart flavor. To produce yogurt, milk is mixed with bacterial culture (containing *Lactobacillus bulgaricus* and *Streptococcus thermophilus*) and the mixture is incubated at 30–45 °C for 4–12 h to allow microbial activity to occur [80]. In Southeast Asia, *dadih* from Indonesia and *tairu* from Malaysia are two identified yogurt-like fermented foods. *Dadih* (Fig. 7A) is a traditional fermented milk popular among people of Minangkabau in West Sumatra, Indonesia. It is made by pouring fresh, raw, unheated buffalo milk into a bamboo tube capped with a banana leaf and allowing it to ferment spontaneously at room temperature for about 2 days [36]. The milk is fermented by indigenous lactic acid bacteria present in the buffalo milk, bamboo tubes, or banana leaves. Traditionally, *dadih* is usually eaten

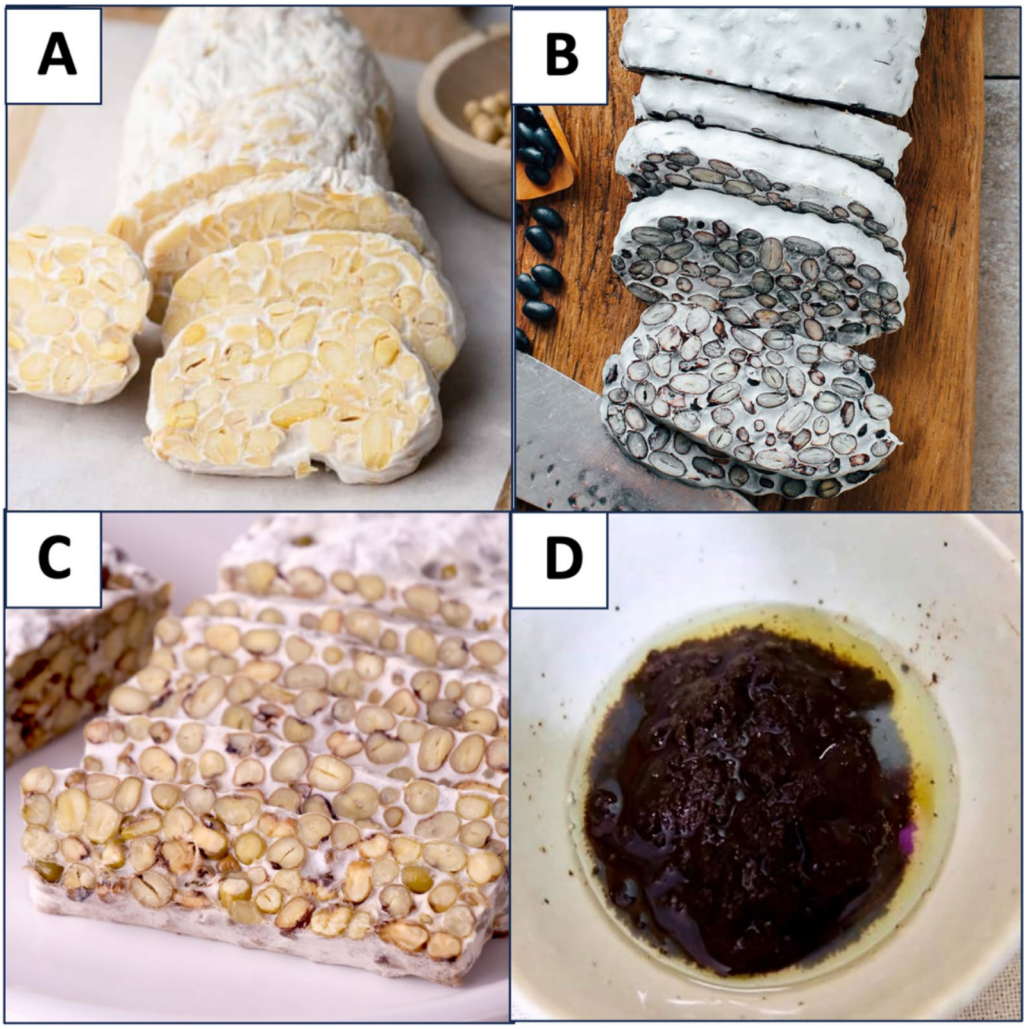

Fig. 6 Fermented food products in Southeast Asia that are derived from legumes: **A** tempeh, a fermented soybean-based food from Indonesia, **B** tempeh made from black beans, **C** tempeh made from mungbeans, and **D** *pon ye gyi*, a fermented paste from Myanmar made from horse gram beans

for breakfast, mixed together with *ampiang* (traditional glutinous rice chips) and palm sugar [81]. *Lactobacillus plantarum* has been identified and reported as the major bacterial isolate found in *dadih* [36, 81]. *Tairu* (also called *taire* or *taina*) is a yogurt-like fermented cow milk from Malaysia [82].

Cheese production also employs microorganisms, in particular lactic acid bacteria producing lactic acid from lactose that curdles the milk. To make cheese, the curd is cut and shrunk by cooking prior to draining or dripping the whey, salting, pressing, and ripening. In Indonesia, *dangke* cheese (Fig. 7B) from South Celebes (Sulawesi) and *dali ni horbo* cheese from North Sumatra are examples of traditionally prepared cheese made from buffalo milk [83, 84]. Interestingly, extract of papaya *(Carica papaya)* leaves is incorporated into the buffalo milk to help curdle milk protein. The extract of papaya leaves contains papain, a protease that works similarly to chymosin in commercial cheese production as a coagulant, creating solid milk curd while releasing liquid whey [85]. Traditionally, *dangke* cheese is molded in coconut shells. *Dangke* cheese has a texture resembling tofu and is further processed through frying or roasting prior to being eaten with rice [83]. In contrast, *dali ni horbo* cheese is generally eaten with local carp dishes cooked in spices [84]. In the Philippines, *kesong puti* is a white soft cheese with salty and sour taste made from the milk of carabao, a species of Southeast Asian water buffalo. It is a popular breakfast food usually eaten with a local bread called *pan*

Fig. 7 Fermented food products in Indonesia that are derived from buffalo milk: **A** *dadih*, a yogurt-like food product fermented in bamboo containers and **B** *dangke* cheese *(keju dangke)* fermented in coconut shells

de sal in the Provinces of Laguna, Samar, Bulacan, and Cebu [86].

Fermented meat-based products in Southeast Asia

Fermented meat products are quite popular in Southeast Asia. Most fermented meat products in Southeast Asia are pork-based, even though in some Southeast Asian countries with a high proportion of Muslims (such as Indonesia, Malaysia, and Brunei), fermented meat products are mainly made from beef. In general, fermented meat products are divided into two categories: those made from whole meat pieces or slices (such as dried meat and jerky) and those made by chopping or comminuting meat (usually called sausages) [40]. In Southeast Asia, most fermented meat products are sausages and there has been no jerky reported.

The basic processes of producing meat-based fermented products, in particular fermented sausages, include meat selection, grinding to facilitate the fermentation process, seasoning (with salt, sugar, spices, and herbs), microbial inoculation, and fermentation [87]. The main microorganisms in the fermentation of meat are lactic acid bacteria and, in some cases, yeasts and molds. *Pediococcus* and *Lactobacillus* are active in producing lactic acid and lowering pH, which helps preserve meat and prevent the growth of spoilage microorganisms and pathogens. Other genus such as *Weissella*, *Leuconostoc*, and *Enterococcus* are also generally present as dominant lactic acid bacteria [88]. Some of these bacteria also produce antimicrobial compounds that enhance preservation in fermented meat, such as bacteriocins and enterocins. During the fermentation process, the beneficial microorganisms metabolize the nutrients in the meat (sugars, protein, and fat), resulting in lactic acid and a plethora of other organic molecules contributing to the complex flavor of the final product. The fermentation process can last from a few days to several weeks or months [88].

Naem or *nham* (Fig. 8A) is a fermented pork sausage in Lao and Thai cuisine. In Laos, it is also popular as som moo. It has a short shelf life and is generally eaten raw accompanied with shallot, ginger, bird's eye chili pepper, and spring onions [89]. Traditionally, *naem* is prepared using minced raw pork and pork skin, significant amount of cooked sticky rice, chili peppers, garlic, sugar, salt, and potassium nitrate (KNO_3) as a curing agent. After the mix is prepared, it in encased in banana leaves or tubular plastic bags and left to ferment for 3–5 days [90]. *Naem* is extensively used in various Lao and Thai dishes, such as *nam khao* (Lao salad dish) and *phat naem sai khai* (naem stir fried with egg) [91]. Interestingly, different regions in Thailand have different flavor preference of naem: north and northeastern *naem* is a little bit sour and southern *naem* is spicy [91]. Today, the quality of *naem* in Thailand is strictly regulated with regard to its bacterial and parasite content in order to ensure food safety [93]. In addition, *naem* is often irradiated [92]. *Chin som mok* is the northern Thai version of *naem* [91]. *Nem chua* is a similar dish originating in Vietnamese cuisine [94].

Sai krok Isaan (Fig. 8B) is a fermented pork sausage originating from Isaan area, the northeastern part of Thailand with a strong influence of Laotian culture [91]. Similar to *naem*, it is also made with pork and rice with other ingredients, including salt, sugar, spices, and herbs. However, instead of using banana leaves to wrap the meat mixture, cleaned pork intestine is used as casing and the

Fig. 8 Fermented food products in Southeast Asia that are derived from meat: **A** *naem*, a fermented pork sausage wrapped in leaves from Thailand, **B** *sai krok Isaan*, a fermented pork sausage in pig intestine from northeastern Thailand, **C** *belutak*, a fermented beef in cow intestine from Brunei, and **D** *bekamal*, a fermented beef from Banyuwangi, Indonesia often served with rice and cooked in bamboo containers

mixture is stuffed inside the casing using a funnel. In this case, the microorganisms naturally present in the intestine also serve as starter cultures for fermentation. Uniquely, *sai krok Isaan* is prepared in bite sizes (approximately 1-inch long) by applying knotted sausage links during stuffing.

In Bali, the only island inhabited mostly by Hindus in the archipelagic Indonesia dominated by Muslims, there is a fermented pork sausage locally known as *urutan*. *Urutan* is made by fermenting a mixture of chopped pork, pork fat, salt, sugar, and unique Balinese mixture of spices and herbs known as *base genep* in pork intestine [95]. *Base genep* consists of local spices widely found in Bali, including ginger, aromatic ginger, greater galangal, turmeric, chili peppers, garlic, shallot, lemongrass, coriander, and candlenut [51]. The presence of such a mixture of spices and herbs gives *urutan* a unique flavor. Since the pork is chopped (not ground), *urutan* has an uneven surface. Traditionally, *urutan* is fermented under the sun for 2–3 days prior to frying for consumption [95].

In Brunei, a Southeast Asian country inhabited mainly by Muslims, and fermented sausage is prepared from beef and known as *belutak* (Fig. 8C). It is an acidic, salty, and chewy sausage made from the small intestine of cows or buffaloes stuffed with a mixture of meat trimmings, salt, and sugar [87]. Following stuffing into casing, *belutak* is fermented at room temperature for 24 h prior to sun drying for at least 5 days [87]. Historically, *belutak* was originally produced by the water village people of Kampung Ayer, considered to be the world's largest water

village, where meat was a commodity not easily available in the past [87]. *Belutak* is usually consumed as a fried side dish during family meals. In Brunei, *belutak* plays a minimal role in the people's daily diet and is considered more like a delicatessen item than a staple food. In addition, *belutak* is also more popular among the water village people than those living on land [87].

Another fermented preparation from beef is *bekamal* (Fig. 8D), a traditional fermented food made from chopped beef, lamb, or goat meat [96]. Bekamal is an ethnic food originally invented by Osing people inhabiting the region of Banyuwangi in East Java, Indonesia. Etymologically, in Osing language, *bekamal* is derived from the word *bek* meaning 'full' and *amal* meaning 'charity,' and thus, the whole word means 'full of charity.' The origin of *bekamal* roots from the Islamic tradition of sacrificing animal on the day of Eid al-Adha or the Feast of Sacrifice, internationally celebrated by Muslims around the world by performing ritual sacrifice of animals in mosques or other public places and sharing their meat with people in need [96]. Due to the abundance of meat following the celebration of Eid al-Adha in Banyuwangi, the Osing people opted for fermentation to preserve the meat to be consumed later. *Bekamal* is traditionally prepared by mixing chunks of meat with palm sugar and salt in a small earthenware jar known as *kendil*. The jar is then enclosed, and the mixture is left to ferment at room temperature for 7 days [96]. In the Osing tradition, *bekamal* is further processed into *nasi bekamal* (*bekamal* rice). *Bekamal* is firstly stir fried with garlic, shallot, chili pepper, and aromatic ginger prior to serving with hot cooked rice [96].

Other fermented food products in Southeast Asia

A few essential fermented food products from Southeast Asia that do not fall under the general categories that were determined previously are placed under miscellaneous fermented products. These food products include fermented tea, egg, chili paste, coffee, and food waste of oil extraction industries.

It has been established that many ethnic people have chewed tea leaves for centuries [97]. In Northern Thailand, an edible fermented tea product called *miang* (Fig. 9A) is chewed as a stimulant. Fresh tea leaves are steamed and kept pressed into sealed bamboo tubes until the anaerobic fermentation (4–7 days) produces a compact cake with the desired astringent and sour taste [98]. The major macroorganisms involved in the fermentation of tea leaves are *Lactobacillus* sp. and fungi [98]. Another type of fermented tea known as *lahpet* in widely consumed in Myanmar, where tea is a major commodity and drinking tea is a national custom [99]. After fermentation, the final form of *lahpet* is flavored with salt, minced garlic, ground chili, lemon juice, and peanut oil. The fermented tea is then eaten as a vegetable incorporated in various dishes [99].

Salted duck egg (Fig. 9B) is a preserved food made by soaking duck eggs in brine or packing each egg in damp, salted charcoal [100]. Originating from China, such a practice has been integrated and adapted in Southeast Asian countries, particularly in the Philippines and Indonesia. The salt enters the eggs from the porous eggshell, while lactic acid bacteria are also involved in the preservation process, thus making the process of salting duck eggs considered as a fermentation. From the salt curing process, salted duck eggs have a briny flavor, a gelatin-like egg white due to protein denaturation, and a firm, round yolk that is bright orange-red in color. In Indonesia, salted duck eggs are popularly known as *telur asin* and widely consumed in Java. The production process includes the making of covering paste from pounded red bricks or *abu gosok* (residual ashes obtained following incineration of organic matters, usually coconut shells) [101]. Some important bacteria that have been isolated in telur asin are *Lactobacillus plantarum*, *Lactobacillus casei* subsp. *rhamnosus*, *Enterococcus gallinarum*, and *Pediococcus acidilactici* [102]. In the Philippines, salted duck eggs are often dyed red to distinguish them from fresh duck eggs [103].

Sriracha sauce (Fig. 9C) from Thailand is a fermented condiment made with red jalapeño chili peppers, salt, vinegar, salt, sugar, and garlic. It originated from the town of Sri Racha in Thailand, and its recipe was created by a Thai woman named Thanom Chakkapak in the 1940s [104]. Sriracha sauce is made by mixing all ingredients together, grinding them to form a homogenous paste, and fermenting the chili paste in a jar for 3–5 days at ambient temperature [105]. Fermenting the chili paste breaks down the carbohydrates and converts them to acid, mainly owing to the activity of lactic acid bacteria [105].

Civet coffee (Fig. 9D), locally known as *kopi luwak* in Indonesia, is a coffee that consists of partially digested coffee cherries which have been eaten and defecated by the Asian palm civet (*Paradoxurus hermaphroditus*) [106]. The cherries are fermented as they pass through a civet's digestive system, and they are collected after being excreted with other fecal matters. Therefore, civet coffee undergoes a series of fermentation in the civet's gastrointestinal tracts, resulting in various components that render the flavor unique and delightful [106]. The civet is thought to select and eat the most ripe and flawless coffee cherries. This selection influences the flavor of the coffee, as does the digestive process. Indonesian civet coffee is currently the second most expensive coffee in the world after Black Ivory coffee extracted from elephant's feces

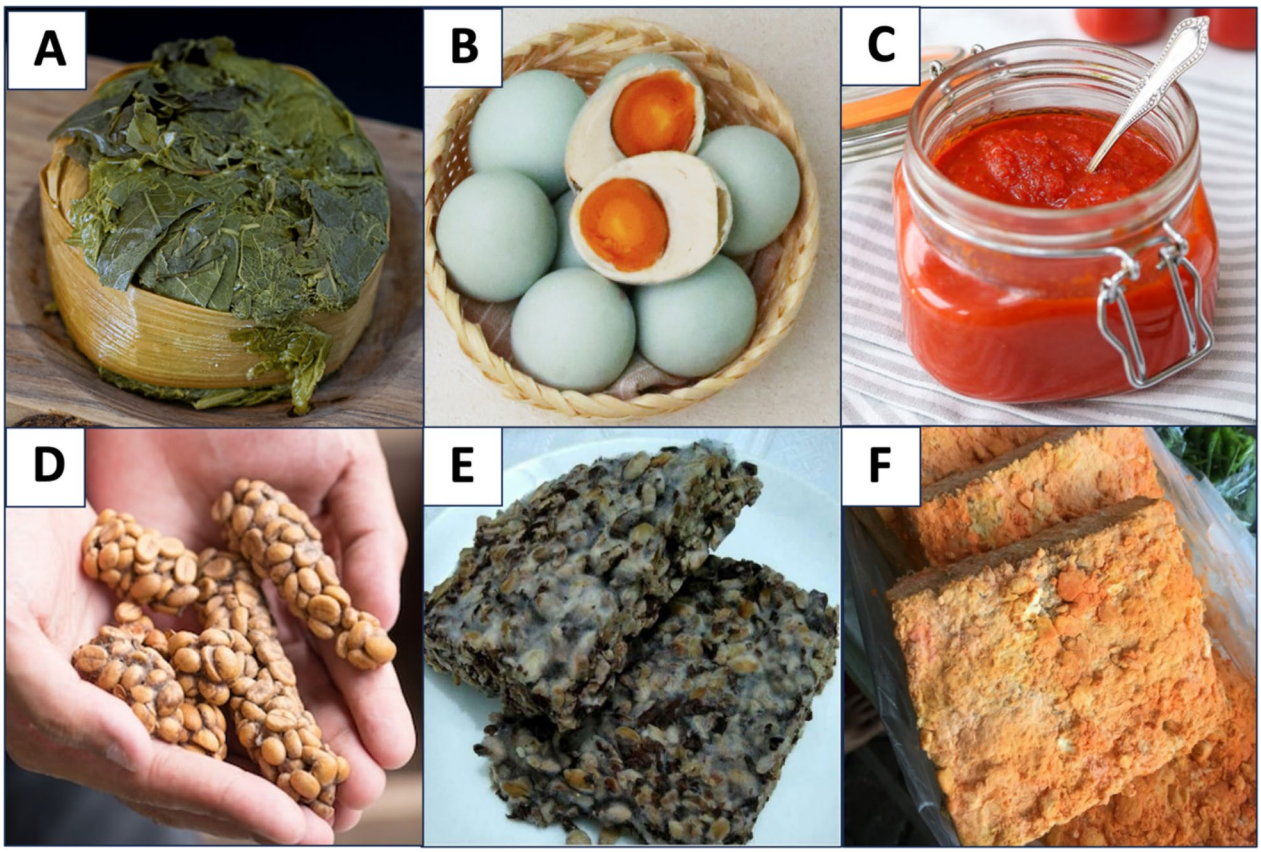

Fig. 9 Other fermented food products in Southeast Asia: **A** *miang*, fermented tea leaves from northern Thailand, **B** salted duck eggs popular in Indonesia and the Philippines, **C** *sriracha*, a fermented chili paste from Thailand, **D** civet coffee or *kopi luwak* grains extracted from feces of Asian palm civet eating coffee cherries, **E** black *oncom* made from peanut press cake using *Rhizopus oryzae*, and **F** red *oncom* made from soybean press cake using *Neurospora crassa*

produced in northern Thailand. Its estimated retail prices reached USD 1,300 per kg wild-collected beans in 2022 [107].

Some fermented food products in Southeast Asian are made from the waste of vegetable oil industries. In the production of vegetable oil, legumes are pressed in the oil press machine, extracting the oil, and leaving the cake as a by-product that still has interesting nutritional values. In Indonesia, the cake by-products left after the extraction of soybean, peanut, coconut, and sesame oil are further processed into nutritious food products through fermentation that are generally called *dage* or *oncom* [108]. There are two popular types of *oncom* based on their color: *oncom hitam* (black *oncom*, Fig. 9E) made from peanut press cake using mold *Rhizopus oligosporus* and *oncom merah* (red *oncom*, Fig. 9F) made from soybean press cake using mold *Neurospora crassa* [109, 110]. *Bongkrek* and *cabuk* are *oncom*-like food products made from fermented coconut press cake and sesame press cake, respectively [33]. *Oncom* can be prepared in various ways. It can be simply deep fried as fritters, seasoned and cooked in banana leaves as *pepes*, or used as fillings for rice dumplings [111].

Discussion

The most remarkable aspect of ethnic fermented foods is that they possess biological health and nutritional benefits due to the functional microorganisms and their metabolites. Today, some of traditional fermented foods are marketed and commercialized as functional foods that provide health benefits beyond their nutritional aspect [112]. Indeed, many fermented foods around the world have been reported to exert many health benefits, such as increasing immunity, preventing cardiovascular diseases, lowering blood cholesterol, providing antioxidants, treating gastrointestinal disorders, and even preventing cancer [113]. Many of these beneficial effects are associated with the presence of some lactic acid bacteria in fermented foods known as probiotics, which are defined as living microorganisms that provide health benefits when ingested [114]. Some examples of probiotics are *Lactobacillus acidophilus*, *Lactobacillus*

plantarum, *Bifidobacterium bifidum*, *Bifidobacterium lactis*, and *Streptococcus cremoris* [114].

Fermented foods offer several advantages compared to unfermented ones in several aspects, including organoleptic, nutritional, and health aspects. Fermentation allows biotransformation into tasty foods with enhancement of organoleptic properties. For example, rice that is generally bland becomes sweet with a hint of alcohol upon fermentation into *tapai*. In general, fermented foods also have a longer shelf life compared to unfermented foods. Fermentation of fruits and vegetables allows preservation without refrigeration or any additional chemical preservatives for several years. Fermentation also results in biological enhancement of nutritional value since many complex nutrients are already digested by microorganisms, thus resulting in higher nutrient bioavailability [40]. In dairy products, lactic acid bacteria degrade lactose into lactic acid and, therefore, fermented dairy products are safe to be consumed by people with lactose intolerance [40]. During fermentation, the activity of lactic acid bacteria also includes the formation of antimicrobial compounds that inhibit the growth of pathogenic microorganisms. For instance, bacteriocins produced by lactic acid bacteria acts effectively against *Listeria monocytogenes* and *Salmonella typhimurium* in fermented sausages [40].

For many ethnic people in Southeast Asia, fermented foods are cheap and accessible source of nutrients. Fermented meat, fish, and legumes are prominent source of protein. Fermented legumes, such as tempeh and other fermented foods derived from by-products (such as *oncom*), allow poor people to have an adequate protein intake [76]. Fermented dairy products provide calcium along with essential vitamins and minerals. Fermented fruits and vegetables are good source of fiber. Together, all ethnic fermented foods have become an integral part of the Southeast Asian food culture for millennia [21]. Fermented alcoholic beverages are consumed during ceremonies and social events, creating a unity among people under one gastronomic identity. In many cases, particularly in villages, ethnic fermented foods are the main source of revenue for many families. Today, most ethnic fermented foods in Southeast Asia are still produced by home industries rather than in big food industries [18].

Despite the interesting nutritional value and health benefits offered by fermented foods, it is noteworthy that some concerns should be taken into account with regard to their regular consumption. Therefore, the safety of fermented foods should be highlighted and emphasized. Regular chewing of fermented tea (such as *miang* in northern Thailand) was reported to be associated with mouth and gastric cancer in the past [115]. In many circumstances, the production process of fermented foods in home industries is poorly controlled and such a phenomenon has been reported to lead to foodborne disease and even death [92]. Some products are considered prone to pathogens when the production process is not rigorously controlled with questionable hygiene, such as fermented meat that is eaten raw [92]. In several cases involving *oncom* made from peanut press cake, poisonous and carcinogenic aflatoxin was detected. This toxin is produced by *Aspergillus flavus*, contaminant molds infecting peanuts [116]. Toxic bongkrekic acid produced by *Burkholderia gladioli* was also found in coconut press cake [33]. Therefore, it is essential to establish safety measures regarding traditional fermented foods to protect consumers. In several Southeast Asian countries, national standards for some ethnic fermented foods encompassing the allowed maximum number of microorganisms and determined physicochemical parameters have been set to ensure the safety and quality of fermented foods [117].

Despite the potential development of fermented ethnic foods as functional foods, research on fermented foods in Southeast Asia is relatively rare and sparse. Overall, scientific studies conducted on fermented foods in Southeast Asia are still in its nascent stages with many areas needing further exploration, thus creating gaps in the literature. Therefore, I would suggest the following areas for additional research and current related problems that require attention: (1) microbial diversity and function: investigating the microbial communities involved in the fermentation processes of lesser-known foods and understanding their specific roles in flavor, texture, and nutritional enhancement; (2) nutritional and health benefits: conducting comprehensive studies on the health benefits of these fermented foods, particularly focusing on their potential probiotic properties, bioactive compounds, and impact on gut health; (3) traditional knowledge and practices: documenting traditional fermentation practices, especially those at risk of disappearing, and evaluating their scientific basis and potential for innovation; (4) safety and quality control: developing standardized methods for ensuring the safety and quality of fermented foods, including the identification of potential pathogens and spoilage organisms; (5) economic and social impacts: assessing the economic viability of fermented foods in local and global markets, and their impact on the livelihoods of local communities; and (6) technological advancements: exploring the application of modern biotechnological techniques to optimize traditional fermentation processes, improve product consistency, and scale up production.

Conclusion

The region of Southeast Asia represents a myriad of ethnic fermented foods that are unique and different from adjacent regions and other regions. The diversity of fermented foods in Southeast Asia cannot only be seen among countries, but also among regions in a country. Ethnic fermented foods have been an integral part of the food culture in Southeast Asia for millennia. These food products encompass a wide range of foods and beverages derived from plants (vegetables, fruits, legumes, starchy ingredients, etc.) and animals (milk, meat, egg, etc.). These foods are valuable assets that should be developed in the future. Gastrodiplomacy with a particular focus on ethnic fermented foods should be strengthened to obtain a wider recognition from other countries. In accordance with this strategy, more scientific studies should be conducted to explore the nutritional and health potential of Southeast Asian fermented foods using novel and innovative tools and methods. Moreover, the traditional knowledge of food fermentation in Southeast Asia also needs disseminating to attract international food researchers to carry out studies on Southeast Asian fermented foods. Such studies are currently lacking, and there is very few information available in reputable international journals. Finally, it appears primordial to regulate the safety aspects of ethnic fermented foods in Southeast Asia to protect consumers. In addition, the production of some popular fermented foods should be shifted from home industry-oriented to mass production by big and certified food industries to expand the market and ensure product quality.

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