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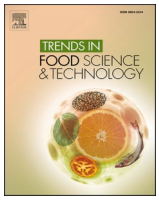

Bamboo shoot and its food applications in last decade: An undervalued edible resource from forest to feed future people

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ABSTRACT

Background: Bamboo shoots, as a representative non-wood forest product, have a long history as a food source and have gained interests from scientists and industry for their potential as a sustainable nutrition resource to address the needs of future populations and ensure food security. Bamboo shoots are abundant in proteins, fibers, minerals, vitamins and many bioactive components, while being low in fat, making them highly valuable in terms of nutrition and health benefits.

Scope and approach: This review comprehensively examines the consumption and processing history, nutritional composition, and potential health benefits of bamboo shoots as a sustainable nutrition resource. It further explores the newly developed functional ingredients and their applications in culinary and other value-added food products.

Key findings and conclusions: Bamboo shoots possess various bioactive components, which contributes to potential health benefits including antioxidant and antimicrobial activities, cancer control effect, prevention of obesity, diabetes, and other diseases. Additionally, numerous functional ingredients such as dietary fibers, polysaccharides, proteins, and antioxidant extracts derived from bamboo shoots have been developed in recent years. Despite their potential, the utilization of bamboo shoots in the current food industry faces limitations, particularly concerning toxicity and sensory aspects that need to be addressed for worldwide consumption. Efforts are recommended to promote awareness, close the knowledge gap, and conduct long-term studies on consumer acceptance of bamboo shoot consumption. Additionally, it is important to overcome challenges faced by the food industry in scaling up shoot-based functional food production. These initiatives will contribute to the broader utilization of bamboo shoots as a sustainable nutrition resource.

1. Introduction

Bamboo, the giant grass belonging to subfamily *Bambusoideae* of Poaceae, is one of the mostly fast-growing and oldest plants on Earth (Wysocki, Clark, Attigala, Ruiz-Sanchez, & Duvall, 2015). As an eco-friendly gift from nature, bamboo could be utilized as wood after maturation or eaten as food when it is a shoot, depending on human's choice. Over 1640 bamboo species within 123 genera are found worldwide, of which more than 1000 species are growing in Asia with a total coverage of 24.9 million hectares, accounting for 71% of world's total bamboo area (FAO, 2020; Singhal, Bal, Satya, Sudhakar, & Naik, 2013; Vorontsova, Clark, Dransfield, Govaerts, & Baker, 2016). China has more than 800 documented bamboo species, of which 153 species produce edible bamboo shoots (Huang, 2021; Li & Kobayashi, 2004). China, being the leading bamboo-producing country, also has the longest history of bamboo shoot consumption as food and medicine. Although, in the past, bamboo was considered as "poor men's timber" in rural areas due to its imprecise processing and underdeveloped utilization (Yu, 2007), bamboo shoots have consistently held their status as a desired health food ingredient in traditional Asian cuisine, available in

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various forms such as fresh, dried and pickled. With increasing attention being paid to the health benefit of shoot consumption, many modern technologies have been applied to the processing of bamboo shoot products including fermentation, roasting, boiling, blanching, canning and pickling (Wang, et al., 2020). The annual per capita consumption of bamboo shoot in Japan has increased from 1.2 kg in 1950s to 3.0 kg in recent years (Santosh Satya, Singhal, Bal, & Sudhakar, 2012), while the import and consumption of bamboo shoot products in western countries has increased more significantly (Wang, et al., 2020; X. Yu, 2007). Despite the increasing popularization of bamboo shoot consumption worldwide, it is still underutilized. For example, China has a total area of 6.4 million hectares of bamboo forests, with only 5.56% and 24.11% for shoot production, and a combined timber and shoot production, respectively (Huang, 2021). It is estimated that 25–35 million tons of bamboo shoots are produced in China annually, with only one third of them are harvested, and mainly consumed in traditional way or processed to be canned or fermented products.

Bamboo shoot is rich in high quality proteins, carbohydrates, minerals and vitamins, but lower fat, which make it an ideal alternative resource of both macronutrients and micronutrients (Satya, Singhal, Bal, & Sudhakar, 2012). With exponential increase in population in coming decades, bamboo shoot, owing to its fast growing and maturation nature, short production cycle and high nutritional value, is believed to be a sustainable nutrition resource to feed future people and ensure food security. Along with the increasing global consumption, trade and production of bamboo shoot, more and more attentions have been paid to the development of shoot-based functional food ingredients, value-added food and pharmaceutical products and applications in last decade (Chauhan, Unni, Kallepalli, Pakalapati, & Batra, 2016; Singhal et al., 2013).

Therefore, this article aims to review the history of bamboo shoot as edible resources and also the processing trends since last century, discuss the nutrients and bioactive compounds in bamboo shoot and their associated health benefits, summarize shoot-based new products and novel utilizations in last decade, and explore the potential and limitation of bamboo shoot as future food.

2. History of bamboo shoot as food

2.1. History of fresh bamboo shoot as food

Bamboo shoot, refers to the aerial bud or meristematic tissue of bamboo plants, is the new culm that just emerge from the ground, with a cylindrical and hollow structure and a cream yellow color (Shima, Inoue, & Sato, 2023). Utilization of edible bamboo shoot for dishes can be tracked back to 3000 years ago in ancient China (Bahru & Ding, 2021; Jiang, 2007). It is considered as one of the most delicious and healthy foods in many other Asia countries. The fresh shoot can be cooked as vegetables. The earliest ancient Chinese dictionary "Erya", which is believed to have been written between the late 4th and early 2nd centuries BCE, has already record the historical origin of bamboo shoots and Chinese cuisine. It describes that "bamboo shoot, the bud of bamboo, can be dishes". Classic of Poetry, the oldest existing collection of Chinese poetry dating from the 11th to 7th centuries BCE, also says that "what vegetables are offered in the dishes? Tender bamboo shoots and cattails" in a chapter of Da Ya. The Rites of Zhou, the classic Confucianism ritual text written in the middle of the 2nd century BC also records that "the utensil called Dou is used to contain pickled bamboo shoots and surimi". All these credible written records confirm the long history of bamboo shoot as food and the common understanding of its delicacy in ancient China. However, not all the bamboo shoots are edible. For example, only 153 species out of 500–800 documented bamboo species in China produce edible bamboo shoots, and only 56 species of them have high quality and are recommended for plantation to meet the international and domestic demands (Li & Kobayashi, 2004). The major bamboo species with edible shoot in the world are summarized in Fig. 1.

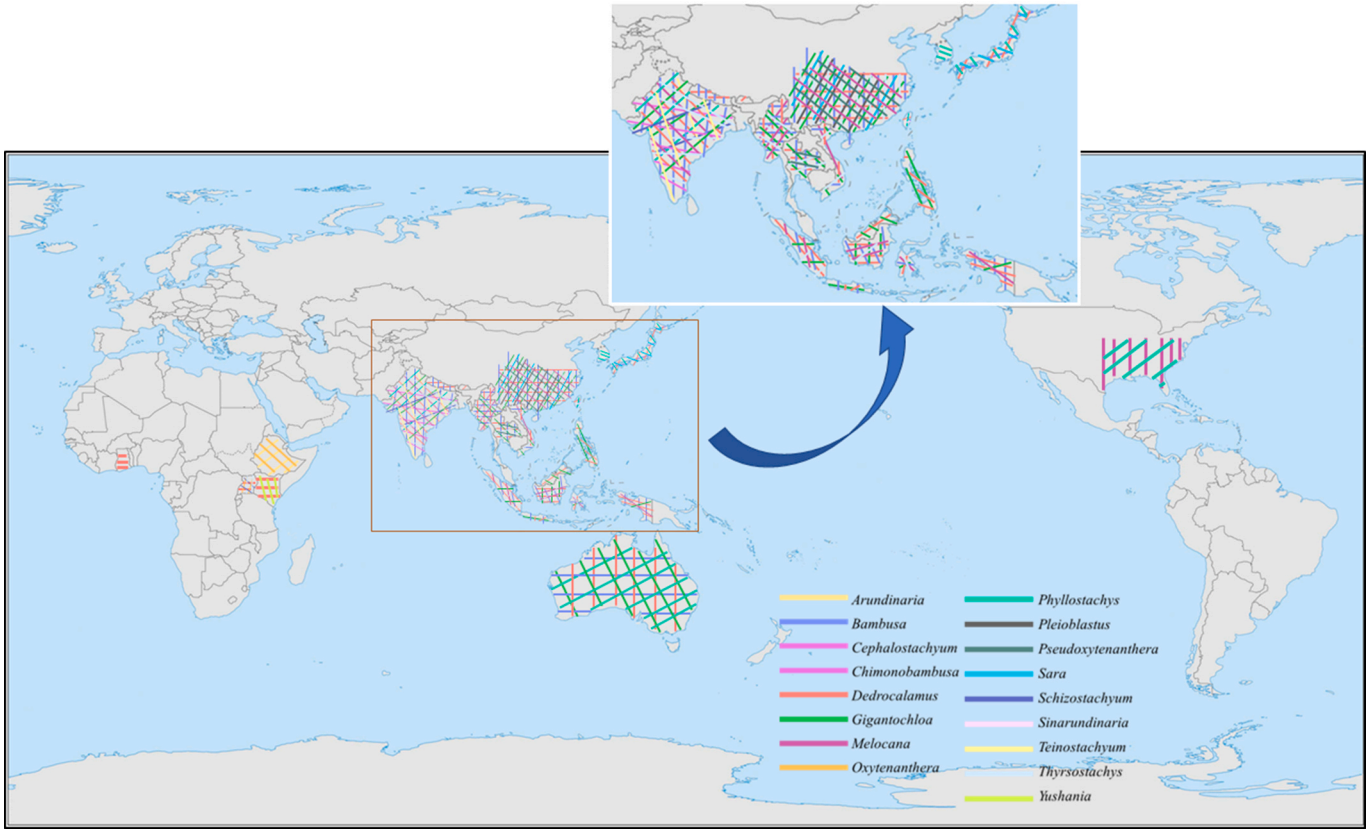

Fig. 1. Species of commercially important edible bamboo shoot in various countries (Adapted from (Chongtham, et al., 2011; Y. Wang et al., 2020)).

As shown in Fig. 1, the edible bamboo species mainly distribute in the Asia-Pacific region, while South American and Africa also grow some species. With the introduction of many bamboo species from Asia, south America and even Africa, the plantation of bamboo in European, North America, and Australia has emerged (Bahru & Ding, 2021). However, most of bamboo shoot products in these regions are imported. The bamboo species including *Phyllostachys edulis*, *Dendrocalamus latiflorus*, *D. brandisii*, *P. praecox* are the main commercial bamboos for shoots in China (W. Liu, Hui, Wang, Wang, & Liu, 2018), while in India, *B. tulda* and *D. hamiltonii* are the main bamboo shoot resources. Several other bamboo species are also commercially significant for their bamboo shoots in Asia. These species include *Dendrocalamus asper*, which can be found in Thailand, Vietnam, Malaysia, Indonesia, and the Philippines. *Bambusa blumeana* is another important species, present in Indonesia, the Malay Peninsula, Thailand, and the Philippines. *B. polymorpha* is native to Bangladesh, Myanmar, and Thailand, while *B. tulda* is also found in Bangladesh, Myanmar, and Thailand besides India. *D. giganteus* is indigenous to India, Sri Lanka, Bangladesh, Nepal, and Thailand, while *Gigantochloa levis* is significant in the Philippines, Eastern Indonesia, and East Malaysia. *D. brandisii* is found in Thailand, and *P. glauca* is mainly in Japan. All these bamboo species play a crucial role in the commercial bamboo shoot industry across Asia. *Oxytenanthera abyssinica* and *Yushania alpina* are the two important bamboo species for shoot consumption in Africa (Bahru & Ding, 2021; Sahoo, Ogra, Sood, & Ahuja, 2010).

The length of the bamboo shoot development stage is primarily

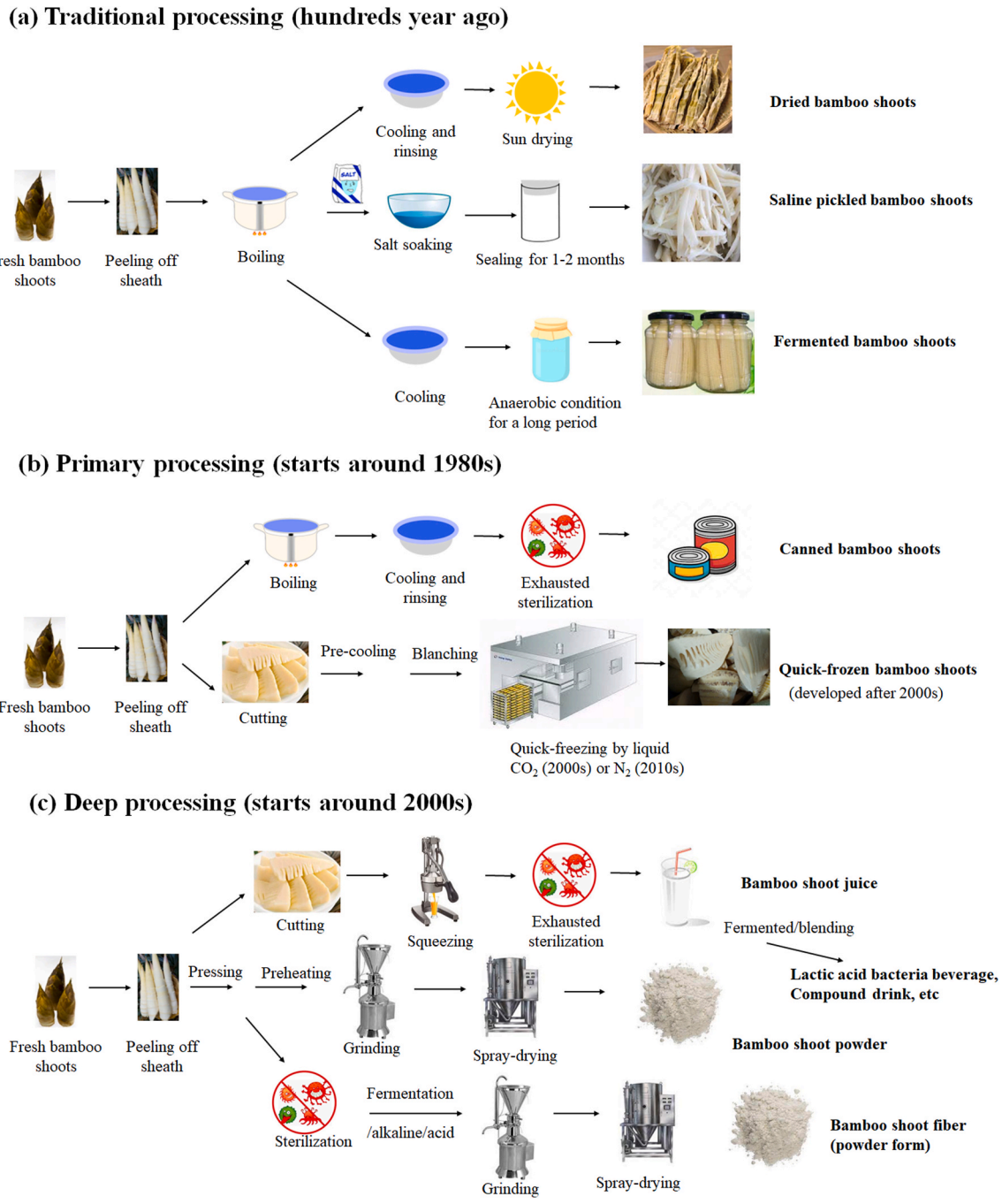

Fig. 2. A processing workflow diagram of bamboo shoot products developed in different stages: (a) traditional processing stage, (b) primary processing stage and (c) deep processing stage.

influenced by temperature. For instance, the average temperature range required for the germination of *Phyllostachys iridenscens* shoots is between 14 and 16 °C (Naixun, et al., 2012). The growth of bamboo shoots from germination to adulthood can vary from 20 days to one and a half months. The levels of endogenous hormones present in bamboo and germinating bamboo seeds, as well as their interactions, also play a crucial role in regulating the growth and development of shoots (Shen, et al., 2020). The edible bamboo shoots are needed to be harvested before they become tough, usually, in the period of March and September for most species every year depending on the variety and location. The delay of harvest may cause the loss of quantity and quality of the bamboo shoot. The fresh shoots may have a strong smell and bitter taste (Chongtham, Bisht, Premlata, et al., 2021). Additionally, the young shoots of many species contain the cyanogenic glycoside taxiphyllin, a toxic compound in nature, which makes the shoots cannot be eaten directly just like other vegetables.

2.2. Evolutionary history of bamboo shoot processing

Fresh bamboo shoot may become lignified rapidly after harvesting, and the color may turn to brown or yellow due to the enzymatic browning resulting from conversion of phenolic compounds to o-quinones (C. Li, Liu, et al., 2019; Z. Luo, Wu, Xie, & Chen, 2012). Different processing strategies have been applied to extend the shelf-life of bamboo shoot with good quality and taste. They could be roughly divided into three stages (Fig. 2). The first stage is called traditional processing stage, in which simple strategies were used to store bamboo shoots in relatively poor living conditions. Fermentation, pickling, solar drying, roasting were the most popular methods conducted by communities in China, India and other Asian countries to preserve bamboo shoots since ancient times (Singhal, Satya, & Naik, 2021; Y. Wang et al., 2020). Spontaneous fermentation dominated by natural Lactic acid bacteria was carried out under anaerobic (Choudhury, Sahu, & Sharma, 2012). Pickling with salt is another technique applied after boiling and slicing. Fermented bamboo shoot pickles have conceited flavor and taste, and were well-accepted as appetizer and chutney in ancient China. Dehydration of bamboo shoot by solar drying or roasting have also been conducted, and the dehydrated bamboo shoot was added into curries by local communities in India and Nepal (Choudhury, et al., 2012).

Due to the rapid growing of bamboo shoot consumption market all over the world, traditional processing methods with relatively high cost and time could no longer meet the demand. Benefiting from the development of modern processing technologies, in 1980s, primary processing technologies such as canning have been used to develop bamboo shoot products, signaled the coming second stage of bamboo shoot processing. The quality and safety of bamboo shoot products could also be better maintained by standardized industrial processing. In this stage, major efforts were contributed to the preservation of bamboo shoot, to extend the shelf-life and keep the nutrients and lower the cyanogenic toxicity (Bal, Singhal, Satya, Naik, & Kar, 2012). It was recommended to boil bamboo shoot at ambient pressure for 20–180 min depending on the canned products, and then cooled, canned, and sterilized (Singhal, et al., 2013). The toxic cyanogenic compounds could be removed by this process, while the uric acid content could be significantly decreased when boiled at high temperatures for a long time (Aichayawanich, Phungamngoen, Wongsa, & Parametthanuwat, 2018). However, long time boiling and the followed sterilization could decrease the vitamin and protein contents of bamboo shoots (Satya, Bal, Singhal, & Naik, 2010). The boiling time could be greatly reduced by heating bamboo shoot in Yanang juice (Phungamngoen & Suwan). The pickling process also significantly decreased the amino acid content of bamboo shoot (Zheng, et al., 2013). Although the storage of bamboo shoot could be extended by these technologies, the nutritional value, texture, and taste of canned and pickled products are significantly reduced compared to fresh bamboo shoot. During the 2000s, the introduction of the quick-freezing process significantly enhanced the storage quality of bamboo shoots. Quick-freezing, also called ultra-rapid freezing, consists in rapidly lowering the inside of the product to a temperature of −18 °C, which could increase the shelf-life of perishable foods with acceptable texture after its thawing (Pruthi, 1999). This technology has been applied on fresh bamboo shoot preservation, to better maintain its original flavor, color, and taste. Carbon dioxide has been commonly used for quick-frozen processing, while liquid nitrogen freezing was applied on bamboo shoot preservation later for high-quality shoot products. To ensure the stable production of quick-frozen bamboo shoots with good quality and safety, the HACCP system was also adopted in the quick-freezing process (Rui-qin, 2012; Xin-ren, Inspection, & Bureau, 2015).

In 2000s, more attentions have been paid to the deep processing technologies of bamboo shoot products as supplementary ingredients. Bamboo shoot juice and powder were either extracted or obtained by mushing and drying, respectively, to be added into food applications as functional ingredients. The advantages of low moisture content, free-flowing, ease of handling and weighing made bamboo shoot powder to be widely used as fiber and carbohydrate source in many food applications (Chauhan, et al., 2016). The bamboo shoot juice could be used to make wine, yoghurt, etc (Sangija & Wu, 2020; YU, NIE, ZHENG, WU, & YU, 2006). In recent decade, the fractions from bamboo shoot such as dietary fibers or proteins were further extracted, purified and used as materials for functional product development. More details will be discussed in a later section.

2.3. Global market of bamboo shoot products

With the increasing demand and interests for bamboo shoots and its products, there has been a 40 % increase in the international trade value of bamboo shoot products over the last decade. The total export trade value of bamboo shoot products with HS Code 200591 was about US$ 230 million in 2007, which increased to US$ 332.9 million in 2018 (Comtrade, 2022). A decline on trade values was found in 2019 and 2020, due to the pandemic of COVID-19. China is the largest exporter with more than US$ 258.9 million exported in 2019, accounting for 89.2% of the world total, while Japan is the largest importer. Bamboo shoot is consumed as a part of traditional Japanese cuisine, and Japan's per capita consumption of bamboo shoots is about 3.0 kg, which is much higher than China's per capita consumption (~0.5 kg) (Santosh Satya, Singhal, Bal, & Sudhakar, 2012; Wu, 2019). Currently, canned bamboo shoot is the main products traded in the international market, accounting for 89% of total export volume. Since more advanced processing technologies (e.g. nitrogen freezing) used in bamboo shoot preservation, the demand for frozen bamboo shoots which have better taste and nutritional value is expected to increase in near future. The innovation on bamboo shoot-based ingredients production could further promote the consumption of bamboo shoot products globally, which will be discussed in following sections.

3. Properties of bamboo shoot

3.1. Chemical composition and structure of bamboo shoot

The structures of bamboo and the cross-section of bamboo shoot are shown in Fig. 3. The shoot is the newly emerged rhizome of bamboo, while bud is the rhizome has yet to reach the surface of soil. Bamboo shoot consists of three parts: sheath, tender bamboo shoot and basal bamboo shoot (Lin, Chen, Zhang, & Brooks, 2018) with its surface covered by many epidermal hairs. The tender bamboo shoot, also called the tip, is the central cylindrical stem after removing a number of sheaths. It is the edible tissue, while the other 70% portion of shoot usually is discarded as waste. The composition of tender bamboo shoot is different to the basal part with higher crude fiber but lower protein content detected in the latter.

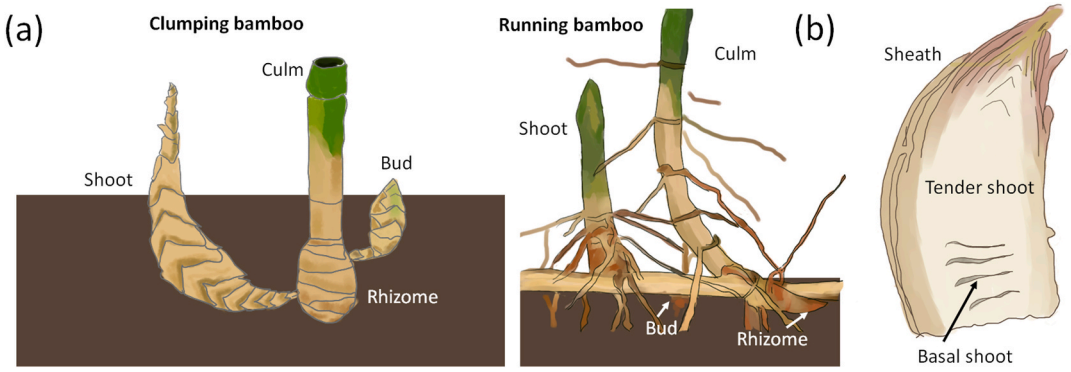

Fig. 3. The anatomy of (a) bamboos and (b) bamboo shoot.

3.2. Nutritional properties of bamboo shoot

The main constituents of macronutrients and micronutrients in fresh bamboo shoots have been summarized in Table 1. Bamboo shoot is a great source of protein and dietary fiber with low starch and fat contents. More details are discussed as below.

3.2.1. Proteins

Bamboo shoot is a great protein source containing at least seven essential amino acids (Lys, Ser, Met, His, Ile, Leu, Phe) for human beings (Wang, et al., 2020). A comparison of the nutritional value of bamboo shoot protein with other major diet protein sources is shown in Table 2. It has been summarized that the protein content in various bamboo shoots is ranging from 1.49 to 4.04g/100 g (Wang, et al., 2020), and 19.01–35.10 g/100 g (S.-y. Xu, Cao, Song, & Fang, 2005) on wet and dry weight basis, respectively. The total protein content of bamboo shoot is similar to cow's milk, with a wet basis of 3.2–3.4%. The essential amino acids (EAA) in bamboo shoot were determined around 30.33–42.53% of total amino acids, which is very close to the EAA proportion of rice and fish (Wang, Wang, Liu, Li, & He, 2011). Bamboo shoot has a much higher protein content than the grains (19.0–35.1% vs 7.5–12%), indicating that a higher amount of EAA could be obtained via bamboo shoot consumption. The protein quality of bamboo shoot strongly depends on species and age (Wang, et al., 2020). The data of bamboo shoot summarized in Table 2 were from 9 common species grown in China. The lowest total and individual contents of EAA were mainly contributed by *Phyllostachys sulphurea*, while the species of *Phyllostachys praecox huangshanensis* showed highest amino acid score of 90.31 (Xu, et al., 2005). It was also suggested that bamboo shoot from low altitude has the higher nutrition quality of protein (Shi, Gu, Chen, Zhang, & Guo, 2019).

Compared with cereals, bamboo shoot protein showed much higher Lys content, which is essential for child's growth and development. Compared with other vegetables, such as cabbage, carrot, celery, and garlic, bamboo shoot showed much higher EAA content (Xu, et al., 2005). Especially, bamboo shoot had abundant Tyr residues, which are limited in most vegetables.

The SDS-PAGE results showed that bamboo shoot had abundant histone-like related peptides and the molecular weights of these peptides were mainly determined in the range of 20.1–15.5 and 29.0–66.5 kDa (Sayanika, Louis, Pranab, & Narayan, 2015). These are highly alkaline proteins, which could expend the storage capacity of DNA and offer the chromatin accessibility with changing internal and external stimuli. While considering the nutraceutical values of bamboo shoot, the high-quality protein is one of the deciding factors to be included in diet, especially for low protein diet.

Table 1
Various macronutrients (g/100 g fresh weight) and micronutrients in tender bamboo shoots (adapted from (Chongtham, et al., 2011; Y. Wang et al., 2020)).

Nutrient	Quantity (g per 100 g fresh weight)
Proteins	1.49–4.04
Carbohydrates	4.32–6.92
Starch	0.21–0.59
Dietary fiber	2.28–4.49
Fat	0.24–0.56
Vitamin C	1.42–3.30
Vitamin E	0.42–0.91
Moisture	89.23–92.51
Ash	0.61–1.38

3.2.2. Carbohydrates and fibers

As the major macronutrient, the carbohydrate content in fresh tip bamboo shoot is around 2.6–6.9 g/100 g wet weight basis (Chongtham, Bisht, & Haorongbam, 2011; Satya et al., 2010), in the form of polysaccharides, oligosaccharides, and monosaccharides. Dietary fibers, especially insoluble dietary fibers including cellulose, hemicellulose, and lignin are the predominated carbohydrates in bamboo shoot. A much higher polysaccharide content value was determined in the sheath and basal bamboo shoots, resulting a crude fiber content of 8.2–37.1g/100 g DW determined in the whole bamboo shoot (Lin, et al., 2018). The fiber content in bamboo shoot increased during maturation or after processing such as canning and fermentation (Nirmala & Sharma, 2008). These polysaccharides were usually discarded as processing by-products, however, have now been used as great source for prebiotics (Chen, Chen, et al., 2018). The polysaccharides can also be hydrolyzed into oligosaccharides and monosaccharides during cooking and processing. Xylan, one of the main components of hemicellulose in bamboo shoot, can be degraded to xylooligosaccharides and xylitol by alkaline extraction to produce functional food ingredients (Yu, Wu, Wang, & Tu, 2014). Some unfavored oligosaccharides such as stachyose and raffinose could also be further degraded to monosaccharides during cooking and processing (Kumbhare & Bhargava, 2007).

3.2.3. Fats

The fat content in bamboo shoot is very low with a range from 0.1 to 3.97 g/100 g fresh wt (Satya et al., 2010). The species such as *Bambusa tulda*, *Dendrocalamus asper* grown in India were found to have the relatively highest fat content (Nirmala & Sharma, 2008). The fat content in bamboo shoot was usually increased with the maturation. As reported, the lipids in bamboo shoot were mainly composed of phospholipids, glycolipids and triglycerides at a ratio of 56:27:17 (Kozukue & Kozukue, 1981). Palmitic, linoleic, and linolenic acids are the main fatty acids. But it was also reported that the unsaturated and saturated fat content in bamboo shoot were 53.97 g/100 g and 16.07 g/100 g, respectively. The high content of sterol and polyunsaturated fatty acid made bamboo shoot oil a good resource to produce functional food with additional health benefits such as hypolipidemic effect (Lu, et al., 2010).

Table 2
Nutritional comparison of the protein with other major protein sources: egg white/milk/grain/vegetable (dry basis/total basis for milk).

Protein source	Protein content (wet weight basis)	Protein content (dry weight basis)	Amino acid concentration (mg/g protein)								Essential amino acids of total AA (w/w %)
			His	Ile	Leu	Lys	Met + Cys	Phe+ Tyr	Thr	Val	
Bamboo shoot	1.49–4.04g/100 g	19.01–35.10g/100 g	5.5–28.6	13.4–62.2	20.5–86.7	18.0–60.0	12.2–45.3	42.1–151.3	10.6–49.5	17.5–67.4	30.33–42.53
Egg albumen	12%	NR	22	54	86	70	57	93	47	66	51.2
Cow's Milk[a]	3.27–3.43%	NR	27	47	95	78	33	102	44	64	50.4
Wheat	NR	12%	21	34	69	23	36	77	28	38	33.6
Rice	NR	7.5%	21	40	77	34	49	94	34	54	41.4
Beef	18%	NR	34	48	81	89	40	80	46	61	48.0
Fish	19%	NR	35	48	77	91	40	76	46	61	44.80–45.92

Data obtained from:(Damodaran & Parkin, 2017; B. Wang et al., 2011); The data that is not reported in the table is indicated by the abbreviation "NR".
[a] Retrieved on 08/21/2022 from Department of Agriculture, Agricultural Research Service, USDA FoodData Central (FDC) with the Standard Reference data released on 12/15/2019 for whole, low-fat and non-fat milk: https://fdc.nal.usda.gov/fdc-app.html#/food-details/746776/nutrients; https://fdc.nal.usda.gov/fdc-app.html#/food-details/746772/nutrients; https://fdc.nal.usda.gov/fdc-app.html#/food-details/746772/nutrients.

3.2.4. Minerals and vitamins

Bamboo shoot is a great source of micronutrients required for human beings including both minerals and vitamins. A comparison has been made between bamboo shoots with various common consumed vegetables (Chongtham, et al., 2011). The content of minerals including K, P, Na, Mg, Ca, and Fe is high in juvenile bamboo shoots. It should be noted that Fe content, a recommended daily consumed mineral for children and pregnant women, in bamboo shoot is the highest among the common vegetables including carrot, spinach, Amaranth, pumpkin, cucumber etc. Bamboo shoots also contained higher amount of Se and K than others except carrot for Se and spinach for K, respectively. However, the content of Se, Fe, and Mg in bamboo shoot gradually decreased during fermentation due to the element migration (Chi, Lu, Liu, & Qin, 2020).

Vitamin C is the most abundant water-soluble vitamin in bamboo shoot, with an average amount of 1.42–3.3 g/100 g fresh weight (Nirmala & Sharma, 2008). It might reach to as high as 23% in a few species. Bamboo shoot also has a good profile of other water-soluble vitamins such as thiamine, niacin and vitamin B6 (Singh, Rathore, & Prakash, 2021). However, vitamin B12, which was believed to be abundant in bamboo shoots, has been found in trace in only a few species or after fermentation (Minh, Vo, Khoi, Hieu, & Le Xuan, 2019). Bamboo shoot contains vitamin A and vitamin E but the amounts are less than other vegetables (Chongtham, et al., 2011). The vitamin C and E content in bamboo shoot was significantly decreased with the maturation. Like other vegetables, the vitamins and minerals decreased significantly after processing such as canning (Nirmala & Sharma, 2008).

3.2.5. Other bioactive components

Bamboo shoot shows great antioxidant properties due to the abundance of phytosterols, carotenoids, and phenolic compounds (Fig. 4). Chongtham Nirmala et al. have summarized different types of nature antioxidants identified from bamboo shoots (Chongtham Nirmala, Bisht, Bajwa, & Santosh, 2018).

Phenols, mainly composed of phenolic acids and flavonoids, are the major nature antioxidants contained in bamboo shoots. It was suggested that the antioxidant capacity of bamboo shoot was highly correlated with its total phenolic contents (Park & Jhon, 2010). The phenolic contents in 4 species of bamboo shoots including *Bambusa balcooa*, *B. tulda*, *D. giganteus* and *D. hamiltonii* were determined, ranging from 191.4 to 505.9 mg/100 g fresh weight (Chongtham Nirmala, Bisht, & Laishram, 2014). However, a highest total phenolic content of 2541.0 mg/100 g wb was reported in *Phyllostachys violascens* (Y. Wang et al., 2020). Protocatechuic acid, *p*-Hydroxybenzoic acid, and syringic acid are the most important phenolic compounds identified in bamboo shoots (Park & Jhon, 2010). The flavonoids, with great potential to be used for treatment of arteriosclerosis, cancer, diabetes, neurogenerative diseases, have been found in the range of 308.72–568.54 μg/g in term of epicatechin equivalent in bamboo shoot (Sonar, et al., 2015).

Carotenoids such as lutein, β-carotene, and zeaxanthin were also detected in fresh bamboo shoot (Kim, Giraud, & Driskell, 2007). However, the total contents of carotenoids were lower than many green vegetables, but were comparable to sweet potato and bracken.

The phytosterols were determined to be mainly composed of β-sitosterol, stigmasterol, campesterol, and cholesterol, ranging from 66.60 mg/100 g db to 242.77 mg/100 g (dry basis) depending on species (Y. Wang et al., 2020; X. Zheng, Chen, Shen, & Yin, 2014). The phytosterol contents increased significantly after fermentation. The discarded portion of bamboo shoots always contain high amounts of phytosterols and phenolic compounds, which have made the residue a good candidate to isolate these bioactive components. However, the bioactive compounds extracted from the bamboo shoot shell differs from the bamboo shoot. The most abundant phenolic compounds in bamboo shoot shell were *p*-coumaric acid, chlorogenic acid, rutin, and ferulic acid (Jiang, et al., 2019). The utilization of bamboo shoot shell extract instead of bamboo shoot may not bring the same biological

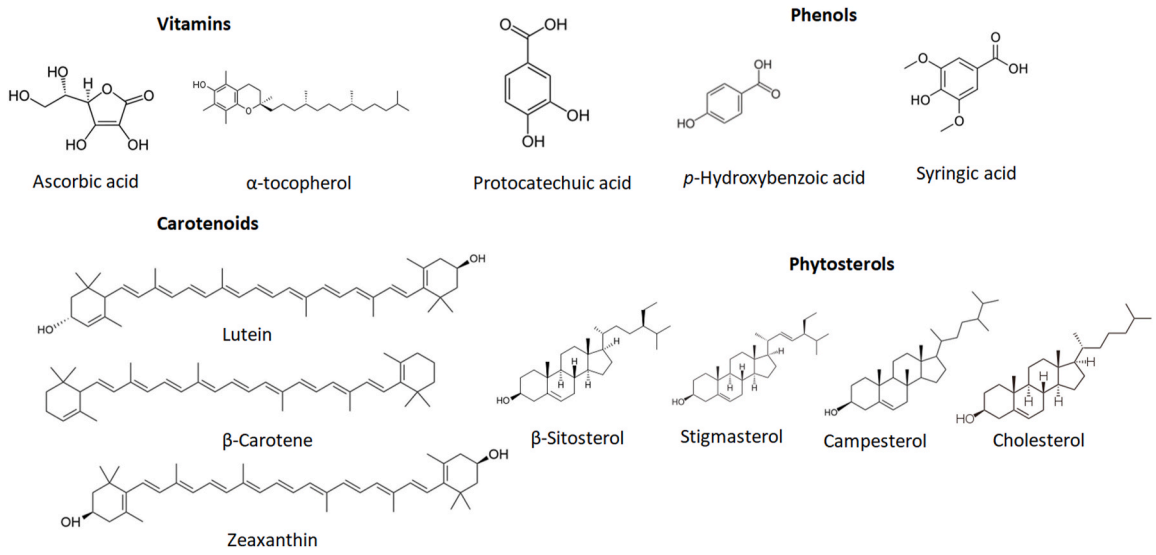

Fig. 4. The most abundant bioactive compounds with superior antioxidant activity in bamboo shoot.

functionality.

3.3. Potential health benefits of bamboo shoot consumption

The consumption of bamboo shoots has been shown to be associated with numerous health benefits, which are detailed in Table 3 and elaborated upon in the subsequent sections.

3.3.1. Antioxidant activity

Antioxidant activity is one of the most important functionalities of bamboo shoot known by people. The phenolic compounds in bamboo shoots could work as scavengers of free radicals, quench ROS and inhibit the oxidative enzymes, and therefore, exhibit strong antioxidant activities. It was suggested that among all the phenolics detected in bamboo shoots, insoluble-bound phenolics showed the most significant contribution to the total antioxidant activity (J. Li, Zhou, & Zhao, 2021). The ascorbic acid, the most abundant water-soluble vitamin in bamboo shoot, could donate a single reducing equivalent, rapidly form monodehydroascorbate and therefore neutralize reactive oxygen species in the aqueous phase as antioxidant (Njus, Kelley, Tu, & Schlegel, 2020). The polysaccharides in bamboo shoot with triple-helix conformation, low molecular weight and glucose content but high reductive hydroxyl groups such as uronic acid units have also been reported to show high antioxidant activities (Chen, Li, et al., 2019). However, while the bamboo shoot extract showed scavenging activity on DPPH radicals attributed to its high phenolic content and other antioxidants (Park & Jhon, 2010), it is important to note that the antioxidant capacities of the extract was found to be significantly lower when compared to commercial antioxidants such as BHT, BHA, and ascorbic acid which are commonly used in food products.

Bamboo shoot has been used as herb medicine since ancient time to treat skin diseases, infections, UV-radiation damage, which mainly relied on its antioxidant and photoprotective activities (Wróblewska, Baby, Guaratini, & Moreno, 2019). In food applications, the addition of bamboo shoot extract or derived ingredients could also lead the antioxidant and preservative functions. For example, the fortification of bamboo shoot extract into food products such as pork nuggets could significantly lower lipid peroxidation and therefore extend the shelf-life (Thomas, Jebin, Saha, & Sarma, 2016). Immerging potato slices into bamboo shoot extract before frying could inhibit the formation of acrylamide, a human carcinogen (Shanmugam, et al., 2016). Obvious differences in variants could be found with *Phyllostachys pubescens* and *Phyllostachys aureosuleata* showed stronger antioxidant activities than others (Curci, et al., 2021). The antioxidant activity of bamboo shoot extract could also be enhanced by new extraction techniques (e.g. microwave-assisted extraction), which has recently received great attention (Milani, et al., 2020).

3.3.2. Antimicrobial activity

Bamboo shoot extracts showed antimicrobial activities against selected food borne and food spoilage pathogens. All the extracts obtained by different solvents showed higher antifungal activity than antibacterial activity as evidenced by lower minimum inhibitory concentrations (MICs) (Kong, Tan, Chye, & Sit, 2020). Bamboo shoot extract at 6% showed great inhibition on *S. aureus*, *Lactobacillus* sp. and yeast and mold counts in pork nuggets and increased the shelf-life (Thomas, et al., 2016).

Although the antimicrobial mechanisms of bamboo shoot extract are still poorly understood, the phytochemicals are believed to be major active components. The phytosterols such as stigmasterol and dihydrobrassicasterol were identified from bamboo shoot skin as the active constituents to inhibit the growth of bacteria (Tanaka, Shimizu, & Kondo, 2013). However, Park and Jhon investigated bamboo shoot extracts from *P. pubescens* and *P. nigra*, and found they showed no inhibition on *E. coli, Ent. faecium, Ent. faecalis*, and *Strep. mutans*, even at 10 mg/mL (Park & Jhon, 2010). These extracts contained high amount of phenolic compounds such as *p*-hydroxybenzoic acid with particularly high antioxidant activity and angiotensin converting enzyme (ACE) inhibitory activity. This result may indicate that other components besides phytosterols may also contribute to the antimicrobial activity of bamboo shoot.

Dendrocin, an antifungal protein, was isolated by Wang and Ng from fresh bamboo shoots (Wang & Ng, 2003). Two peptides, namely Pp-AMP 1 and Pp-AMP 2, with antifungal and antibacterial activities were also isolated from *Phyllostachys pubescens*, and they showed a high degree of homology to mistletoe toxins with plant defensin common structure features (Fujimura, Ideguchi, Minami, Watanabe, & Tadera, 2005). A polysaccharide with molecule weight of 5.77×10^3 Da extracted from bamboo leaves also showed obvious growth inhibitory against *E. coli, S. aureus* and *B. subtilis* in range of 0.50–50.0 mg/mL (Xiao, et al., 2020). The pickled bamboo shoot also showed antimicrobial activities, which was attributed to the antimicrobial compounds produced by lactic acid bacteria during fermentation (Hartayanie, Lindayani, & Murniati, 2016). The above studies confirmed the effectiveness of bamboo shoot extract as antimicrobial for potential functional food applications. However, the antimicrobial activity of bamboo shoot is much lower than

Table 3
Health benefits of bamboo shoots and the resultant applications in food.

Health benefit	Responsible bioactive components	Mechanism	Substrate	Applications	Activity indicator for application
Antioxidant activity	Phenolic compounds, ascorbic acid, vitamin E, etc.	Free radical scavenger	Bamboo shoot extract	Namkeen snack (Oinam Santosh et al., 2021)	Reduced IC_{50} of DPPH
				Pork nuggets (Thomas, et al., 2016)	Reduced lipid oxidation
				Fried potato chips (Shanmugam, et al., 2016)	Reduced acrylamide formation
	Reductive hydroxyl groups in chains	Reductive hydroxyl groups, low molecular weight and glucose but high amounts of uronic acid with triple-helix conformation	Bamboo shoot-derived polysaccharides	Functional ingredients (Chen, Li, et al., 2019)	High oxygen radical absorbance capacity (ORAC) value, radical species scavenging
	Phenolic compounds	Free radical scavenger	Bamboo shoot shell	Extracts as functional ingredients (L. Jiang et al., 2019)	DPPH and FRAP assay
Antimicrobial activity	Phytosterols, antifungal proteins/peptides, and polysaccharides	NR	Bamboo shoot extract	Pork nuggets (Thomas, et al., 2016)	Increased shelf-life from 21 days to 35 days at refrigeration storage
	Lactic acid bacteria		Fermented bamboo shoot	Pickled bamboo shoot (Hartayanie, et al., 2016)	Inhibited growth of *E.coli* and *S.au.*
Hypolipidemic and antihypertensive effect	Phenolic compounds, flavones, and glycosides	ACE inhibitory	Bamboo shoot oil or ethanol extract	Supplementary with diet (Lu, et al., 2010; Octaviani, 2020)	Decreased the levels of total cholesterol, relative liver weight and liver lipids; decrease blood pressure
Prevention of obesity and fatty liver disease, bowel function improvement	Dietary fibers	Gut microbiota modulation	Bamboo shoot and extracted dietary fibers	Supplementary with diet (E.-J. Park & Jhon, 2009); Fortification for functional foods (Oinam Santosh et al., 2019; Setiawati et al., 2022)	Lower cholesterol levels and improve bowel function
	Lactic acid bacteria		Fermented Bamboo shoot	Lactic acid bacteria beverage, compound red jujube drink (Zhao, et al., 2021)	Viable cell count
Anticancer effect	Phenols, phytosterols Sterol-glucoside-fatty acid derivative	Regulation of ROS Apoptotic activity by the upregulation of proapoptotic genes (P53; Bax; and caspases 3, 8, and 9) and downregulation of the antiapoptotic genes (Bcl2)	Bamboo shoot extract	Several cancer types such as cancers of the breast, lung, colon, rectum, thyroid, and leukemia (Sharma & Nirmala, 2018)	The inhibition of malignant tumors in mice model
	Terpenes	NR		Prevention cancers such as prostate cancer (J.-S. Kim et al., 2014)	
Prebiotic activity	Fibers (polysaccharides)	Gut microbiota modulation, probiotic promotion	Bamboo shoot fibers, bamboo shoot residues	Supplementary ingredient (W. Wu et al., 2020)	Short chain fatty acids detection and microbial genomic technology
Anti-inflammatory activity	Alkaloids, phenolic compounds	Regulation of the extracellular regulated protein kinase signaling pathway.	Bamboo shoot extract, shell	Gout treatment (Mustaffa, Mansur, & Kassim, 2022)	Reduction in inflammatory markers

The content that is not reported in the table is indicated by the abbreviation "NR".

bamboo leaf and shell, and is strongly dependent on the species and extraction solvent (Anselmo-Moreira, Gagliano, Sala-Carvalho, Grombone-Guaratini, & Furlan, 2021; Zhu, Zhang, Lo, & Lu, 2005). To only achieve antimicrobial function, using bamboo shell or leaf might be more cost-effective and efficient than bamboo shoot.

3.3.3. *Prevention of obesity, diabetes, and other diseases*

Using bamboo shoot as a traditional medicine to treat or prevent several diseases such as cardiovascular disease, paralysis, hypertension has a long history in China, India and many other countries and areas and still prevails nowadays (Wang, et al., 2020). It has also been used to treat wound healing, kidney diseases and extensively for treating gynecological disorders in certain places (Kalita & Dutta, 2012).

The consumption of bamboo shoot in diet could significantly lower cholesterol levels and improve bowel function in healthy young women, thanks to the high fiber content (Park & Jhon, 2009). To confirm that, bamboo shoot fibers were extracted and fed to the mice with high-fat diet directly, and a significant reduction of the levels of triglycerides, blood glucose, total cholesterol, high-density lipoprotein, and low-density lipoprotein was found (Li, Guo, Ji, & Zhang, 2016; J. Yang, Wu, Yang, & Pan, 2021). The prevention of the obesity and fatty liver disease by bamboo shoot fiber was relevant to its modulation on gut microbiota and host metabolism. A recent study found that insoluble bamboo shoot dietary fiber and soluble dietary fiber exhibited the hypoglycemic effects through complicated and different pathways (Zheng, et al., 2019). A supplementary of sufficient amount of total dietary fiber from bamboo shoot with diet was recommended for the individuals at risk for or diagnosed with diabetes.

Bamboo shoot oil extract with high sterol content was also found to inhibit cholesterol absorption and increase cholesterol excretion, showing pronounced hypolipidemic effects as a novel vegetable oil (Lu, et al., 2010). It was also suggested that many protection effects of bamboo shoot against many chronic and degenerative diseases were mainly attributed to the content of phenolic compounds, flavones, and glycosides (Chongtham Nirmala, Bisht, & Laishram, 2014). The ethanol extract of bamboo shoot at a dose of 40 mg/kg was most effective to decrease blood pressure of male mice than other high dose intake groups (Octaviani, 2020). The hypotensive effect of bamboo shoot oil extracts was attributed to the phenolic acid and flavonoid contents, which showed dose-dependent inhibitory activity on the angiotensin converting enzyme (ACE) (Park & Jhon, 2010). The water extracts of fresh and canned bamboo shoots also showed ACE inhibitory, which were

attributed to the ascorbic acid content and bioactive peptide fractions (Liu, Liu, Lu, Chen, & Zhang, 2013; Park & Jhon, 2010).

3.3.4. Cancer control effect

It was suggested that the oxidative stress was associated with many cancers, and therefore, the high content of phenols and phytosterols in bamboo shoot has made it a potent candidate to therapeutically treat cancers (Le Goff, et al., 2019). The anti-cancerous activities of bamboo shoots or bamboo extracts have been demonstrated by many recent studies (Sharma & Nirmala, 2018). The steam extract from *P. bambusoides* and *P. pubescens* showed good cytotoxicity against PC-3 cells, indicating a potential to treat prostate cancer (J.-S. Kim et al., 2014). The monoterpenes (62.96%–71.36%) and sesquiterpenes (23.58%–33.13%) were identified as the main compounds in the extract. The extract of Sasa veitchii also induced the apoptosis of a human breast cancer cell line (MCF-7 cells) at low doses and necroptosis at high doses (Ichimaru, et al., 2020). The apoptosis of tumor cells by many phenolic and phytosterol compounds was related to the regulation of ROS (Le Goff, et al., 2019). Phytosterols could increase the antioxidant enzymes including manganese SOD and the GSH-Px, and therefore protect cells from damage caused by ROS. The trigger of the depolarization of mitochondrial membrane potential and also increasing the Bax/Bcl-2 ratio in cell could be another pathway for anticancer effect of these phytosterol compounds.

Apart from the common phenolic compounds, a sterol-glucoside-fatty acid derivative was isolated from *Phyllostachys heterocycla* var. pubescens showing stronger cytotoxic against the MCF-7 cells with IC_{50} of 25.8 μM compared to fluorouracil (26.98 μM), a model anticancer drug molecule (Abdelhameed, et al., 2020).

It was found that the consumption of dietary fiber showed positive effect on reduction of colon cancer (Kaczmarczyk, Miller, & Freund, 2012). As a fiber-rich source, bamboo shoot is a great source to improve the digestion function with potential to inhibit colon cancer. A recent study showed that moso bamboo (*Phyllostachys edulis*) shoot polysaccharide significantly decreased the level of *Fusobacterium* (Li, Zhou, & Zhao, 2021). This bacterium is commonly found in the colons of individuals with gastric cancer. These findings highlight the remarkable potential of bamboo shoots in reducing the risk of such cancer. This benefit upon bamboo shoot fiber consumption is also discussed in the following section.

3.3.5. Prebiotic activity

Recently, the role of prebiotic fibers in the positive modulation of gut microbiota has come to the forefront, since the dysbiosis of the gut microbiota is believed to be associated with a number of metabolic disorders and diseases. The prebiotic fiber is defined as nondigestible carbohydrate polymer that beneficially affects the host by modulating the composition and/or activity of the gut microbiota after its metabolization in the gut (Carlson, Erickson, Lloyd, & Slavin, 2018). Bamboo shoot contains a large number of polysaccharides which are non-digestible in the upper gastrointestinal tract, and therefore has gained great interests recently on its impact on host metabolism and the gut microbiota (Li, et al., 2016). Compared with cellulose, the bamboo shoot fiber feeding markedly increased relative abundance of *Bacteroidetes* and strongly inhibited *Verrucomicrobia*, two divisions strongly correlated with body weight. The isolated water-soluble polysaccharides from bamboo shoot increased the numbers of *Bifidobacterium adolescentis* and *Bifidobacterium bifidum*, demonstrating their prebiotic activity on the proliferation of bifidobacterial (He, et al., 2016). However, in a more recent study, the impacts of insoluble dietary fiber and soluble fiber from five different fresh bamboo shoots (*Phyllostachys praecox, P. edulis, Fargesia spathacea, P. pubescens,* and *P. iridescens*) on gut microbiota were compared. And it was found that, although soluble fiber showed stronger probiotics promotion effect, supplement of insoluble fiber was more effective in enhancing the production of short chain fatty acids, which play key roles in regulating host metabolism and the immune system (Wu, et al., 2020). In this regard, there are also many interests on using bamboo shoot residues after processing to extract fibers as a cost-effective and environmental friendly solution for prebiotic purpose (Chen, Li, et al., 2019).

3.3.6. Other extended benefits

Thanks to the presences of different bioactive components contained in bamboo shoot, many other extended health benefits have also been claimed. The crude extract from *Phyllostachys heterocycle* and the *Pleioblastus amarus* showed potent anti-inflammatory activity by suppressing the activation of the extracellular regulated protein kinase signaling pathway, and therefore downregulating the production of proinflammatory mediators and cytokines (Ibrahim, et al., 2021; Ren et al., 2019). This beneficial effect may be attributed to the presence of total alkaloids in the extracts (Ren, et al., 2019). The oral administration of the fresh bamboo shoot juice showed immunomodulatory activity on rats, indicating a potential material for immunosuppressive drug development (Thathsarani, Jayasinghe, Jayawardena, & Nilakarawasam, 2021). It also enhances the function of calcium that helps regulate heart beat and potassium balance besides the control of hypertension. There are already many commercial bamboo based products with the additional health benefits such as anti-aging, anti-fatigue, simulation of collagen synthesis in bone claimed in these nutraceutical products (Chongtham Nirmala, Bisht, Bajwa, & Santosh, 2018).

4. VALUE-ADDED/NEW food applications based on bamboo shoot in last decade

In last decade, the application of bamboo shoot and the derived ingredients in the food industry has been widespread. Especially, with increasing demand of food for well-being and health by customers, extensive attention has been paid on bamboo shoot recently to develop functional foods, which have been described in detail in the following sections. Some examples of the resultant food applications are also summarized in Table 3.

4.1. Functional ingredients derived from bamboo shoot

4.1.1. Dietary fibers and polysaccharides

Recently, the supplementary of dietary fiber with diet has caught the attention of nutritionists throughout the world to improve human health. Adding dietary fiber into various food applications has become an attractive strategy for food industry to produce functional foods. Bamboo shoot is a rich source of dietary fiber, and therefore, has been used to extract different dietary fibers or individual polysaccharides as functional ingredients directly.

The dietary fiber from bamboo shoots in the form of powder and paste has already been used for the fortification of various food products, such as biscuits, fish ball (Zeng, et al., 2016), milk pudding (J. Zheng, Wu, Dai, Kan, & Zhang, 2017), and pork salt-soluble proteins (K. Li, Liu, et al., 2019), as discussed in the above sections. As shown in Fig. 5, the addition of bamboo shoot fiber at a low dose increased the aggregation of particles (Fig. 5b), resulting in a more compact microstructure of the milk pudding. However, at a high dose, it could damage the structure due to induced flocculation (Fig. 5c). The dietary fibers could be further separated into insoluble and soluble fibers based on the water solubility (Fig. 5 d and e). The surfaces of insoluble fibers typically exhibit a loose and porous structure with a complex spatial network. In contrast, the surfaces of soluble fibers appear smooth and consist of small particles. Fresh bamboo shoots were blended to slurry after shelled and washed. After hot water incubation, treatment of α-amylase and protease, and several round of hot water washing, the insoluble dietary fiber could be obtained by freeze-drying the residues (W. Wu et al., 2020). The soluble dietary fibers could then be gotten by treating the filtrate with alcohol separation, followed by centrifugation, rehydration and lyophilization. Many soluble bamboo shoot polysaccharides could

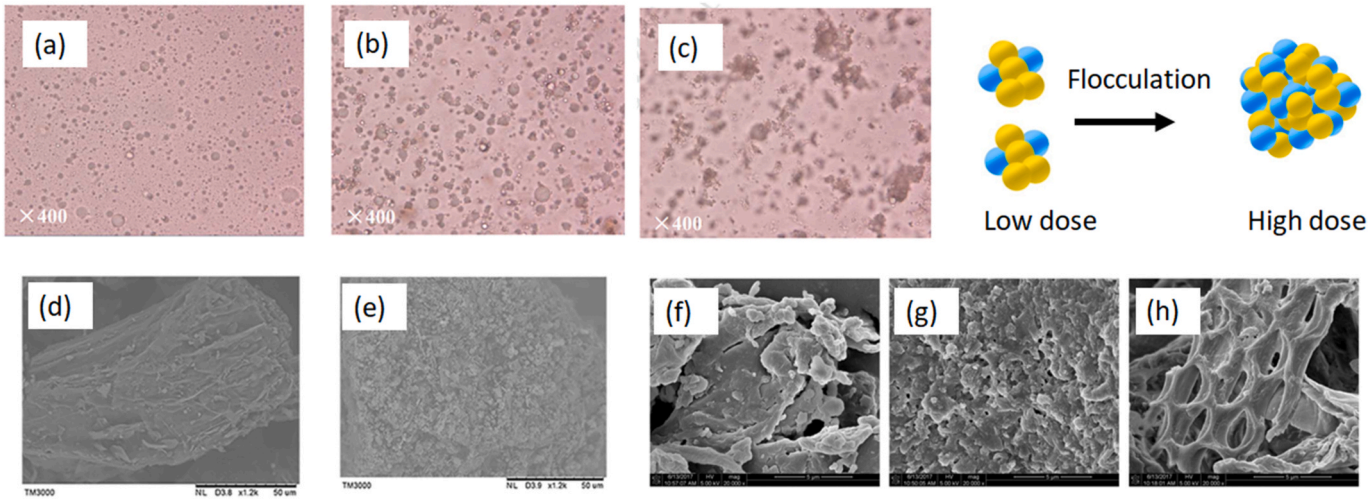

Fig. 5. Microstructure of milk pudding compound system without (a) and with bamboo shoot dietary fiber at (b) low dose and (c) high dose (J. Zheng et al., 2017); The insoluble dietary fiber (d) and soluble dietary fiber (e) extracted from bamboo shoot *P. pubescens* (W. Wu et al., 2020); The bamboo shoot shell insoluble fiber without (f) and with further enzyme treatment (g) and high-pressure micro-fluidization (h) (X. Luo et al., 2018).

also be obtained by water extraction and dehydration of bamboo shoot residues. Bamboo shoot (Chimonobambusa quadrangularis) residue-derived polysaccharides were obtained (9.96 g/100 g db) and exhibited DPPH and hydroxyl radical scavenging ability (Chen, Bu, et al., 2018; Chen, Li, et al., 2019). Additional enzymatic hydrolysis could be further used to produce fiber hydrolysates with enhanced water solubility and antioxidant activity (Karnjanapratum, et al., 2019).

More and more researchers have been engaged in the exploring the use of the processing waste of bamboo shoot such as the bamboo shoot shell to produce dietary fibers. Young bamboo culm has also been suggested as alternative source for dietary fiber extraction (Felisberto, Beraldo, & Clerici, 2017). Although bamboo shoot shell has been demonstrated as an excellent and low-cost source of polysaccharide and dietary fiber, it is mainly composed of cellulose, hemicellulose and lignin, and therefore, required additional techniques such as enzyme treatment and high pressure micro-fluidization (Fig. 5 f-h) to further improve their properties before application (Lu et al., 2018). However, the traditional extraction by mechanical method would cause the damage to the equipment and result in high energy consumption. Additional decoloration step on shell waste is also needed to get a final product with good appearance. Therefore, using bamboo shoot shell to obtain dietary fiber and other functional ingredients is still at infant stage.

4.1.2. *Protein derived from bamboo shoot*

Bamboo shoots are a valuable source of plant-based protein with high-quality, making them a promising option for protein extraction and the development of functional ingredients. The conventional extraction using alkaline and the deep eutectic solvent extraction using ChCl:levulinic acid at various ratios have been conducted to recover proteins from bamboo shoots and its processing wastes (Lin, Jiao, Zhang, Celli, & Brooks, 2021). The protein yield from fresh bamboo shoots was 23.9 mg/g and 39.2 mg/g dry basis by alkaline and deep eutectic solvent, respectively. The yields from processing waste including basal bamboo shoot and sheath were much lower. Individual functional peptides and proteins have also been isolated from fresh or fermented bamboo shoots (L. Liu et al., 2013; H. Wang & Ng, 2003). Although the utilization of bamboo shoots to produce protein ingredients or functional peptides is just emerging, these studies are very useful for the development of protein ingredients and the applications by food industry. The protein extracted from bamboo shoot or processing waste may also be a good protein resource to produce healthy treat for pet feed.

4.1.3. *Antioxidant extracts*

Bamboo shoot extracts by alkaline, oil, methanol or other organic solvent always show great antioxidant and antimicrobial activities, and have been added into food applications as described in Table 3 and the above sections. Using the bamboo shoot processing waste to extract phenolic compounds-enriched fractions is another strategy to add the value to bamboo shoot by-products. For example, phenolic compounds enriched extracts with high antioxidant activity could be obtained from bamboo shoot shell by using 58% ethanol or hexane as solvent (Jiang, et al., 2019). These antioxidant extracts from processing by-products could be used for some pharmaceutical and cosmetic applications. However, the direct utilization by food industry was still limited due to the lack of data on characterization and safety.

4.2. *Fermented bamboo shoot*

Fermentation is a traditional way for bamboo shoot processing. Fermented bamboo shoots have palatable flavor, aroma and texture, and are more digestible (Singhal, Singh, Satya, & Naik, 2017). In addition, fermentation is considered to be the best technique to remove the cyanogen and oxalate contents in bamboo shoot and provide the long shelf-life (Chongtham, Bisht, Premlata, et al., 2021). Therefore, many efforts are still devoted to fermented bamboo shoot, to further improve its sensory, shelf-life, and nutritional values. A pre-treatment of boiling bamboo shoot in 10% NaCl solution for 35 min was found to be the best method to reduce the cyanogen and improve the overall acceptable for a bamboo shoot pickle (Shinde, Sawate, Kshirsagar, & Patangare, 2019). The bacterial diversity in non-salt fermented bamboo shoots with natural spring water was investigated, and *Weissella, Lactobacillus*, and *Lactococcus* were determined to be the dominant genera and played vital roles, but in the later fermentation phase, the latter two were the dominator (J. Xu, Jiang, & Fan, 2020). In another study, using *Exiguobacterium aurantiacum* FB6-1 b instead of traditional fermentation has been recommended for the production of Soibum, a traditional food in India, which could improve the nutritional quality of the fermented bamboo shoot (Khunjan, Pandey, & Sharma, 2018).

Many antinutrients in bamboo shoots could be removed during fermentation. However, the antioxidant activity of bamboo shoot flour was also significantly reduced after 48 h fermentation by lactic acid bacteria due to the reduction of total phenol and total flavonoids (Putri, Iwansyah, Desnilasari, & Kumalasari, 2020). In some other studies, the therapeutic properties of the bamboo shoots were improved after fermentation (Chongtham, Bisht, Santosh, Bajwa, & Indira, 2021).

Using fermented bamboo shoot to extract dietary fibers or other functional ingredients is another main targeted technique studied in recent years (Do, et al., 2020; Zeng et al., 2016). The exopolysaccharides produced by lactic acid bacteria strains isolated from fermented bamboo shoot have aroused great interests and numerous efforts have been devoted to enhance the yield of these functional exopolysaccharides from fermented bamboo shoot (Do, et al., 2020).

4.3. Shelf-stable bamboo shoot

With the advancements in drying and preservation technologies, such as quick-frozen and high hydrostatic pressure (HHP) technology, the quality of long shelf-life bamboo shoot products has significantly improved. This is especially evident in the case of water bamboo shoots treated by HHP, where the activities of enzymes involved in lignin and cellulose polymerization and accumulation, including phenylalanine ammonia lyase (PAL), were reduced (Miao, Wang, Zhang, & Jiang, 2011). Consequently, these treated shoots exhibited reduced firmness. The cold plasma treatment has also been applied on fresh-cut bamboo shoot, which not only extended its shelf-life but also inhibited the development of unpleasant aromas (Liu, et al., 2023). Furthermore, this treatment has helped maintain the characteristic green and sweet fruity odors of the bamboo shoot.

4.4. Bamboo shoot beverage

Functional bamboo shoot-based beverages have been developed using fresh bamboo shoot juice, fermented shoots, or shoot-derived ingredients. One such beverage is bamboo wine, which is made from the fermented shoot juice of *Oxytenanthera abyssinica* (Sangija & Wu, 2022). This wine is not only rich in water-soluble B vitamins and essential and nonessential amino acids but also contains various antioxidants, including free radical scavengers and anti-aging agents. Moreover, composite beverages with health benefits have been created by blending bamboo shoot juice or extract with other fruit and vegetable juices or Chinese herbal medicine extract. As an example, bamboo shoots were mixed with red jujube fruits and fermented, resulting in a new beverage that exhibited high nutritional value, high antioxidant capacity, and a high dietary fiber content (Zhao, Du, Li, Du, & Wang, 2021).

4.5. Bakery and fried products

Bamboo shoot juice and powder have been used as ingredients for fortification of bakery products due to the health promoting properties of the abundant bioactive components. Bamboo shoot was grinded and added as fortification to make functional food products such as namkeen (an India snack) with enhanced antioxidant activity (Oinam Santosh, Bajwa, Bisht, & Chongtham, 2021). The IC_{50} of DPPH was significantly improved from 2824.24 μg/mL to 2100.95 μg/mL in this formulation. Functional biscuits were made by replacing 20% of wheat flour with paste of fresh shoots, with a significant increase in the amount of proteins, phenols, phytosterols, vitamin C, and dietary fiber contents in the functional biscuits (Oinam Santosh, Bajwa, Bisht, & Nirmala, 2019). Converting bamboo shoots into powder for food fortification is more convenient. The functional biscuits made by replacing 10% wheat flour with boiled and freeze-dried bamboo shoot powder were enriched with nutrients, bioactive compounds, and minerals (O Santosh, Bajwa, Bisht, & Nirmala, 2018). Notably, sensory evaluation revealed that the fortified biscuits had improved acceptability compared to biscuits made with freeze-dried powder without the boiling process. Fiber-enriched modified flour has also been made with a combination of bamboo shoot and nagara tuber flour as alternatives to formulate the wheat flours for functional food (Setiawati, et al., 2022).

The physical quality of the deep-fried batter could be improved by the addition of bamboo shoot fibers. The color, viscosity, and coating and frying yield of batter with bamboo shoot fiber were significantly improved compared with control fried batter and fried pork loin (Park & Kim, 2021).

4.6. Meat products

Bamboo shoot extract at 6% was incorporated into pork nuggets, and showed significant improvement on the microbiological quality, sensory parameters, and lipid oxidation prevention (Thomas, et al., 2016). The incorporation of fermented dietary fiber derived from bamboo shoots into battered and breaded fish balls could significantly reduce the fat absorption during deep-fat frying by providing a more compact structure with smaller pore size (Zeng, et al., 2016). In another study, bamboo shoot fiber was added into the batter of fried pork loin, which increased the water content, decreased the fat content, achieved higher viscosity, coating yield, and frying yield, and showed similar sensory characteristics with control fried pork loin (S.-Y. Park & Kim, 2021). In these applications, the addition of bamboo shoot or bamboo shoot fibers could reduce the fat content and improve the quality, which were mainly relied on the microstructure and mechanical properties of fibers, and their cross-linking to improve the pork protein network (K. Li, Liu, et al., 2019). Therefore, bamboo shoot and derived fibers are promising in the processing of meat products.

4.7. Other novel utilizations of bamboo shoot

The fibers isolated from bamboo shoot may be used not only as diet supplementary for nutrition purpose, but also as functional ingredients due to their unique physical properties. Pickering emulsion stabilized by solid particles is highly promising in food applications because of its outstanding stability against coalescence. The insoluble fibers from bamboo shoot have been used to prepare oil-in-water pickering emulsions, which showed great stability against high ionic strength, acidic pH, and mild heating temperature (He, Li, Li, Li, & Liu, 2020). The bamboo shoot fiber prepared nanoparticles are attractive emulsion stabilizers to be applied to various food systems directly.

Modified bamboo shoot cellulose and β-cyclodextrin were cross linked to produce pH-sensitive hydrogel, which exhibited higher drug release ratio in simulated intestinal liquid than in gastric liquid (Liu, Luo, & Huang, 2016). Composite aerogels were prepared using bamboo shoot cellulose as major encapsulant, which showed successful sustained-release function of curcumin (Zhang, et al., 2021). The fibers from bamboo shoot and the processing waste could be chemically modified to nanocrystals, nanoparticles with various morphologies (Li, Zhou, & Zhao, 2021; Wijaya, Ismadji, Aparamarta, & Gunawan, 2019). These indicate that bamboo shoot fiber could be a promising material to develop controlled delivery system for functional foods.

5. UTILIZATION limitations of bamboo shoot in current food industry

5.1. Toxicity

Some toxics such as cyanogenic glucoside (taxiphyllin) are contained in raw bamboo shoots, which could release cyanohydrin acid (HCN) when fresh bamboo shoot is macerated as in chewing. The metabolic pathway of cyanogenic glycosides in bamboo shoots is shown in Fig. 6 (Møller, 2010; Y. Wang et al., 2020). The cyanogenic toxicity of bamboo shoot could be significantly reduced to safe level during processing, such as boiling, fermentation, and drying (Bal, et al., 2012). It was suggested that the HCN content in fresh *Dendrocalamus asper*. Was 29.36 ppm (Darmajana & Wulandari, 2019), and the HCN in bamboo shoot flour could be reduced to 4.86 ppm after 20 min baking. The cyanide content was also reported to decrease substantially following harvesting. When the consumed dose of HCN is relatively small, the molecule of HCN could be detoxified into thiocyanate by the enzyme of rhodanese, and then excreted in the urine (Satya et al., 2012). So proper processing on

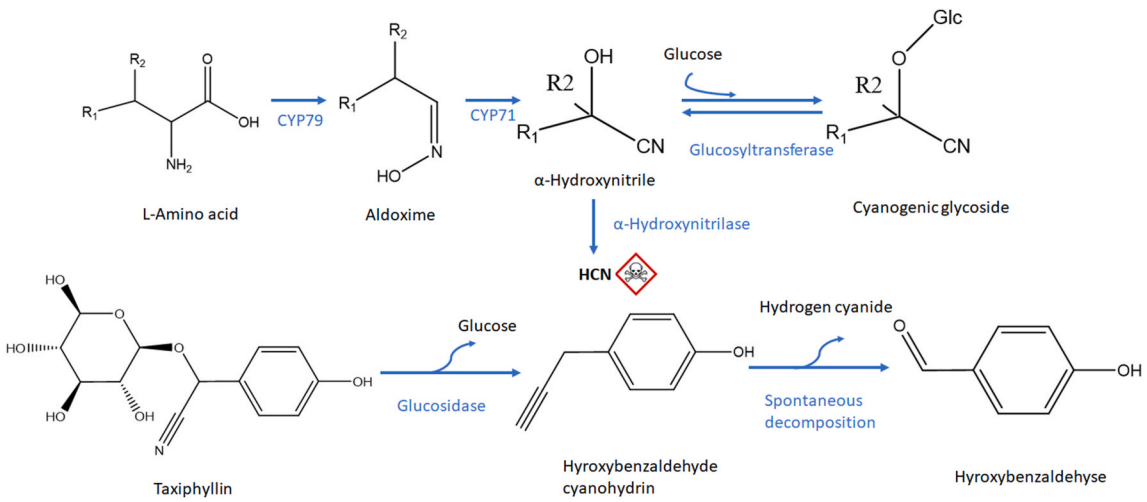

Fig. 6. The metabolic pathway of cyanogenic glycosides in bamboo shoots: biosynthesis (up) and biotransformation (down) (Møller, 2010; Y. Wang et al., 2020).

bamboo shoot should be carried out and the toxic content should be tested before putting the product on the market.

There are also some other concerns regarding the safety risk of high dose consumption of bamboo shoot extract as functional ingredients. Although a high dose up to 1600 mg/kg body weight of bamboo shoot extract feeding for a long period (up to 28 days) showed no damage on the histoarchitecture of liver and kidney of mice, the level of serum creatinine, glutamic pyruvic transaminase, and lactate dehydrogenase increased significantly (Bajwa, Santosh, Koul, Bisht, & Nirmala, 2019). An investigation on the efficacy and safety of long-term bamboo shoot consumption is still recommended.

5.2. Sensory

As processed food products, bamboo shoot displays distinctive taste and flavor, which is very favorable for customers. As functional ingredient, bamboo shoot powder and fiber usually could improve the sensory attributes of baked food such as the texture (Mustafa, Naeem, Masood, & Farooq, 2016; Tamayo & Tamayo, 2020). Nonetheless, in some cases, the bamboo shoot powder and derived fiber are expected to have plain flavor and taste, which would not affect the sensory properties of the food application itself. The bamboo shoot ingredient obtained by different processing methods may show different impacts on the aroma and taste of food applications. For example, the namkeen fortified with 24 h soaked shoots showed lower sensory attributes than that fortified with 20 min boiled shoots (Oinam Santosh et al., 2021). Some species such as *Gigantochloa atter* have carrot-like color, which may change the original appearance of the fortified food (Caasi-Lit, Mabesa, & Candelaria, 2010). These changes should also be considered before new bamboo shoot-based ingredients reach the market.

5.3. Postharvest preservation and shelf-life quality

Rapid browning and lignification of postharvest bamboo shoot often happen, leading to a deterioration of quality and the loss of commercial value (Bal, et al., 2012). A prolonged storage could also cause the significant increase of cellulose and lignin content in bamboo shoot. It was suggested that the browning caused by increased peroxidase (POD) activity could also be inhibited by low-storage temperature (Xiao-li, Xiao-ping, Meng-yun, & Jin-jun, 2008). The lignification could also be retarded at 4 °C. To minimize the deterioration of quality, processing and storage at low temperature and low oxygen conditions are recommended. However, the cost of currently-used equipment such as vacuum cooling was high and the sugar content in bamboo shoot might decrease during preservation. More advanced preservation methods with low cost are still urgently needed.

5.4. Variations with species

Bamboo shoots from different species and geographical locations may exhibit varying sensory attributes, nutritional content, and physicochemical characteristics. Therefore, when using bamboo shoot powder or extract as ingredients, it is important to consider their variations in nutritional content and physicochemical properties. For example, in terms of fiber content, *M. baccifera* was found to have the highest crude fiber content at 35.5% (Bhatt, Singh, & Singh, 2005), making it a suitable source for fiber ingredients. On the other hand, different species of bamboo shoots have varying antioxidant activity. Fresh shoots of *D. strictus*, *B. tulda*, *B. vulgaris*, and *B. balcoa* were found to possess antioxidant activities of 13.97%, 15.94%, 28.21%, and 39.85%, respectively (Satya, Singhal, Prabhu, Bal, & Sudhakar, 2009; Singhal et al., 2013). Among these species, *B. balcoa* displayed the strongest radical activity and is recommended as the main bamboo shoot resource for the development of ingredients with antioxidant properties in India. In this regard, further exploration and systematic comparisons are needed not only to assess the nutritional values but also to evaluate the sensory and culinary characteristics of different bamboo shoots, particularly when they are used as bioactive ingredients in functional products. Such research would be highly advantageous for screening suitable species for the cultivation and processing of bamboo shoots, thereby contributing to the growth of the local economy.

5.5. Ecological and socioecological risks

Whether native or exotic to a region, bamboo has the potential to become invasive in fragile areas. To mitigate this risk, it has been suggested that forests with greater plant diversity are more effective in preventing erosion and sediment production compared to exclusive bamboo forests (Buziquia, Lopes, Almeida, & de Almeida, 2019). Actually, harvesting bamboo shoots timely is an effective practice to prevent the unintended spread of bamboo. However, when introducing bamboo to a new area, continuous monitoring is necessary, along with the establishment of suitable environments for bamboo shoot consumption and processing. These measures would be helpful to minimize the risk of suppressing the stages of ecological succession in local vegetation and avoid changes in forest structure and diversity.

6. Conclusion and perspective

Bamboo shoots, as a typical non-wood forest product (NWFPs) and

an underestimated natural resource in the international scenario, have great potential to become a mainstream food worldwide and contribute to United Nation's Sustainable Development Goals. This potential stems from several aspects.

i) *Feeding future people as a high-quality food resource.* Globally, approximately three billion individuals lack access to nutritious diets (Cheek, et al., 2023). Sustainable Development Goal 2.1, to be achieved by 2030, aims to end hunger and ensure access to safe, nutritious and sufficient food for all people, particular the poor and people in vulnerable situations. Fig. S1 presents a co-occurrence clustering analysis of keywords related to sustainable food resources, bamboo shoot, and sustainability. Further information on the co-occurrence clustering analysis and the discussion on bamboo shoot and other sustainable forest foods can be found in the Supplementary Discussion. Generally, bamboo shoots, primarily found in developing countries, can play a crucial role in addressing local food shortage, as staple diet with balanced nutritional value. Their high-quality protein and fiber content make them a promising food source that can both nourish people and improve their overall health.
ii) *ensuring sustainable food supply as eco-friendly NWFPs.* Bamboo, being a fast-growing wild plants, is a remarkable and eco-friendly resource gifted from forests. Its rapid growth rate and ability to regenerate after harvesting make bamboo shoots a solid candidate for the development of future food products. Particularly in economically disadvantaged regions with forest cover, such as Africa, bamboo shoots hold immense potential to serve as mainstream food, thereby contributing to local economies and addressing global food security challenges.

Overall, bamboo shoots have demonstrated their potential as a future food source that can satisfy both nutritional and sustainability requirements. Consequently, they have received great interests from scientists and industry in accelerating their utilization and application. However, it is important to note that widespread acceptance of bamboo shoots as a staple food or common food ingredient worldwide may require some time. More efforts are recommended to be put into below areas to achieve the integration of bamboo shoots into global food systems.

(1) Promote awareness on bamboo shoot consumption and close the knowledge gap

Meeting increasing food demand to feed future people with limited agricultural land is a worldwide challenge. One potential sustainable solution to achieve the "zero hunger" goal set by the United Nations is to incorporate forest foods, such as bamboo shoots, into our diets. With the great interests to increase the forest area globally for sustainable development, the total area of bamboo forests increased by 50% between 1990 and 2020, particularly in China, India and other developing nations (FAO, 2020). Taking Africa with the third largest distribution area of bamboo resources in the world as an example, more than 115 bamboo species and a total bamboo area of 4.65 million hectares are reported across 48 African countries (FAO, 2020), the continent accounts for 7% of the world's bamboo species and 12% of the global bamboo resource (Bahru & Ding, 2021). However, the utilization and processing of bamboo shoots in these areas are currently very limited or underdeveloped. In fact, many these bamboo shoot-producing countries in these areas have never been harvested shoots, resulting in untapped food resources. This situation is further exacerbated by the lack of awareness among consumers and the general public regarding the benefits of bamboo shoots. Thus, it is crucial to increase efforts in cultivating the market and educating the public about the consumption of bamboo shoots. This includes recognizing the cumulative knowledge and practices rooted in the cultural traditions of regional, indigenous, or local communities. Such efforts are essential for promoting the cultivation of bamboo resources and the development of products based on bamboo shoots. Additionally, fostering partnerships between individuals, private enterprises, and local governments can facilitate and expedite this process.

(2) Overcome challenges for food industry to scale-up shoot-based functional food production and promote the utilization of shoot-based ingredients

As discussed in above sections, some drawbacks on the utilization of bamboo shoot such as the cyanogenic glucoside toxicity, undeveloped harvest and preservation protocols still exist. The variations in properties and nutritional qualities among different bamboo shoot species could potentially hinder the utilization of bamboo shoots or the establishment of standardized processing methods. It is critical to overcome these difficulties for efficient industrial development of shoot products and shoot-based novel functional foods. In this regard, it is necessary to establish international standard protocols to regulate the cultivation, harvest and processing of bamboo shoots, and therefore to ensure the quality and safety of bamboo shoot and their products. At current stage, the bamboo shoot production and processing are of considerable importance in Africa, provide integral part for supporting local economies. However, the processing and utilization of bamboo shoots in these areas, like many other Non-Wood Forest Products (NWFPs), suffer from inefficiency, lack of eco-friendliness, and unsustainability. It is crucial to develop improved approaches for these forest foods to promote and expedite sustainable development and investment in forests and forestry. One potential direction for optimizing bamboo cultivation and enhancing its local economic viability is through inter-planting local herbs or edible fungi within bamboo forests, particularly in young bamboo plantations (Lu, et al., 2018).

With the increasing demand of health food with high nutrition values and the fact of food shortage to feed growing number of people, more research efforts from food scientists and collaboration with private sectors are expected to be devoted to remove these technical barriers, to achieve the goal of accelerating the development of bamboo shoot-based foods at multiple industrial levels.

Although many studies have been done on the incorporation of bamboo shoot-based ingredients in culinary and novel functional applications, there is a lack of long-term studies on consumer acceptance on these shoot-based ingredients, especially in non-traditional markets. This lack of information could hinder the widespread use of bamboo shoot as a mainstream ingredient. Therefore, it is also important for researchers to focus on studying consumer acceptance of functional applications using bamboo shoot ingredients. By understanding consumer preferences and attitudes towards these products, the food industry can better tailor their offerings to meet consumer demands and accelerate the adoption of bamboo shoots as a versatile ingredient.

(3) Promote the integration of bamboo shoot industry with the development of local economics

Compared to traditional timber trees that require decades to mature, bamboo has a rapid growth rate, enabling sustainable and continuous production of shoots without depleting natural resources. This characteristic of bamboo offers the potential for sustainable food resources and creates opportunities for trade and export, which can contribute to the growth of local economies. We suggest that local governments should be encouraged to plan and establish modern bamboo shoot food industrial parks that encompass various aspects such as production, research and development, finance, logistics, storage, tourism, and offline and online markets. Additionally, future research should delve deeper into the ecological footprint, socio-economic implications, and potential trade-offs associated with large-scale bamboo shoot production.

Contributions

Yue Zhang: Writing- Original draft, editing; Liangru Wu: Conceptualization, Writing-Reviewing and Editing; Yanxia Li: Writing-reviewing and editing; Jinlai Yang: Writing-reviewing and editing; Huiming Yang: Writing-reviewing and editing; Yihe Zhao: Writing-reviewing and editing; Guangjing Chen: reviewing and editing.

Ethics declarations

The authors report there are no competing interests to declare.

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Appendix A. Supplementary data

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