Food and Bioprocess Technology (2018) 11:901–912
https://doi.org/10.1007/s11947-018-2088-3

REVIEW

Potential for Value-Added Utilization of Bamboo Shoot Processing Waste—Recommendations for a Biorefinery Approach

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Received: 14 June 2017 / Accepted: 23 February 2018 / Published online: 7 March 2018

Abstract

Bamboo shoot processing produces substantial quantities of wastes in China and other parts of the world, with estimates of up to 70% of the harvested bamboo shoots being discarded as waste biomass. The solid waste residues that are generated as processing by-products consist of the outer sheath and basal section of the bamboo shoot, and wastewater is also produced, all of which pose a significant environmental burden. In comparison to the edible bamboo shoot tips, data on the composition of bamboo shoot processing residue (BSPR) are comparatively scarce. The tender shoots are rich in nutrients and bioactive compounds that are associated with health benefits against many chronic and degenerative diseases, and there is potential for these compounds to also be present in BSPR. Therefore, this paper reviews the current literature available on BSPR composition from both English and Chinese journals, for comparison with the tender bamboo shoot. From this information, the potential of using BSPR as a cheap source of valuable nutrients and bioactive compounds for value-added products (e.g., food additives, functional foods, and pharmaceuticals) is discussed. To maximize the value from BSPR and reduce its environmental impact as a waste, a systematic biorefinery approach for waste valorization is recommended.

Keywords Bamboo shoots · Processing waste · Nutrients · Bioactive compounds · Waste utilization

Introduction

Bamboo is a perennial, giant, woody grass belonging to the family Poaceae. There are more than 1250 species of bamboo, which grow in humid tropical, sub-tropical, and temperate regions, especially in Asia, Latin America, and Africa (Devi 2013; Devi and Pamba 2015; Sangeetha et al. 2015). Bamboo shoots appear as newly emerging tender stalks from a network of rhizomes and are rich in proteins, carbohydrates, minerals, vitamins, phenolic compounds, and phytosterols (Devi and Pamba 2015). In many Asian countries, such as China, Japan, Korea, Taiwan, Thailand, and Philippines, bamboo shoots are consumed as part of the local cuisine and are also used as a traditional medicine (Chandramouli and Viswanath 2012; Panee 2015). China is the largest producer of bamboo shoots, producing around five to six million tons of bamboo shoots annually (Chen et al. 2012b), followed by India and Japan (Bal et al. 2012). While 40% of the bamboo shoots are consumed fresh, the rest are usually processed into dried, canned, boiled, marinated, fermented, and medicinal forms (Bal et al. 2012; Chandramouli and Viswanath 2012; Chen et al. 2012b).

The whole bamboo shoot consists of three parts, sheath, tender bamboo shoot (tip), and basal bamboo shoot, as shown in Fig. 1. Bamboo shoot processing typically produces huge quantities of waste residues as by-products, with up to 70% of the harvested bamboo shoot discarded as waste and only 30% being consumed (Chen et al. 2012b). The bamboo shoot processing residue (BSPR) consists of the overlapping and non-edible leaf sheaths that cover the edible tender part of the bamboo shoot, as well as the basal portion of the bamboo shoot, which is composed of tough woody fiber (Satya et al. 2010; Devi and Pamba 2015). In addition to the BSPR (i.e., sheaths and basal parts), processing water, which includes

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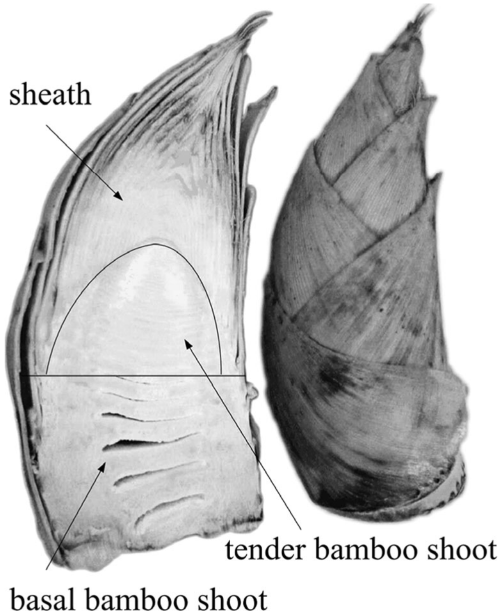

Fig. 1 Diagram of a bamboo shoot, showing the edible tender tip and waste bamboo shoot processing residue (BSPR) consisting of the sheath and basal parts

water used for boiling, soaking, and chilling, is also a by-product of commercial bamboo shoot processing (Chen et al. 2012b). This can be a significant waste stream with approximately 2 t of wastewater produced with every ton of processed bamboo shoots (Liu et al. 2013). The typical processing diagram of ready-to-eat canned bamboo shoots and the waste residues produced are shown in Fig. 2.

There has been much research on the processing, composition, and health benefits of extracted compounds from the edible parts of the bamboo shoot (Satya et al. 2010; Chandramouli and Viswanath 2012; Singhal et al. 2013; Nirmala et al. 2014; Panee 2015). The data on BSPR is extremely limited in comparison; however, according to Chen (2014a), the sheath and basal part of the shoot are similar in composition to the tender shoot. Based on the antioxidant activity and bioactive components present in the edible bamboo shoot (Nirmala et al. 2014; Devi and Pamba 2015; Panee 2015; Sangeetha et al. 2015), there is potential for BSPR to be used as a raw material for extracting compounds with high nutritional value and associated health benefits such as nutraceuticals or nutritional supplements and as ingredients in functional foods. This would create value from a significant waste stream and reduce the environmental impact incurred when disposing of this waste, which is an important consideration as BSPR is high in moisture and protein content and has a short production season (Chen 2014a). Thus, in this review, we report on the common ways that BSPR are currently disposed of and utilized. This is followed by an overview of the available literature from English and Chinese journals on the composition of BSPR in relation to the edible bamboo shoot and then a discussion of the results from specific studies. The bamboo species mentioned in this review include *Phyllostachys bambusoides*, *P. heteroclada*, *P. sulphurea*, *P. iridenscens*, *P. praecox*, *P. meyeri*, *P. pubescens*; *phypramiens*, *P. tianmuensis*, *P. violascens*, *Dendrocalamus latiflorus*, *Pleioblastus amarus*, *Pleioblastus juxianensis*, and *Pleioblastus maculatus.* Finally, the future prospects for advanced BSPR utilization are discussed in terms of a biorefinery approach and recommendations for further research are made.

Current Management of BSPR

Current management of the BSPR is through disposal and conversion to traditional products of low-added value and animal feed (Chen 2014a). In this section, these current uses of BSPR are described.

Disposal

At present, most of the BSPR is disposed of through incineration or by direct dumping into the environment (Ye et al. 2014). Direct land disposal requires that sufficient space is available, and when untreated BSPR is disposed of, there can be undesirable consequences, such as the emission of unpleasant odors, breeding of mosquitoes, and leachate outflow. Composting is another waste management technique; however, environmental persistence of the BSPR is problematic due to their antibacterial properties, and natural degradation of the residues may require more than 2 months (Su et al. 2013).

Traditional Products and Uses

Bamboo shoot residues can be used to produce a variety of items in China such as handicrafts and toys, flooring materials, door curtains, footwear and soles, hats, furniture, and disposable tableware. These products are popular with consumers around the world (Yu and Wang 2010; Chen 2011; Yu et al. 2012). In addition, bamboo shoot sheaths have been traditionally used as a container to maintain the taste of tea in China and are used as effective packaging materials for rice balls and meat in Japan, due to their antibacterial properties (Xu and Cai 2006; Tanaka et al. 2011).

Animal Feed

BSPR is not suitable for direct consumption as food for humans, as it is tough and fibrous. However, it is also rich in protein, vitamins, minerals, and other bioactive compounds. In comparison to common straw, which is used as animal feed, the nutritional value of BSPR is higher (Zeng and Yue 2015a). The use of BSPR as animal feed is hindered by the seasonal

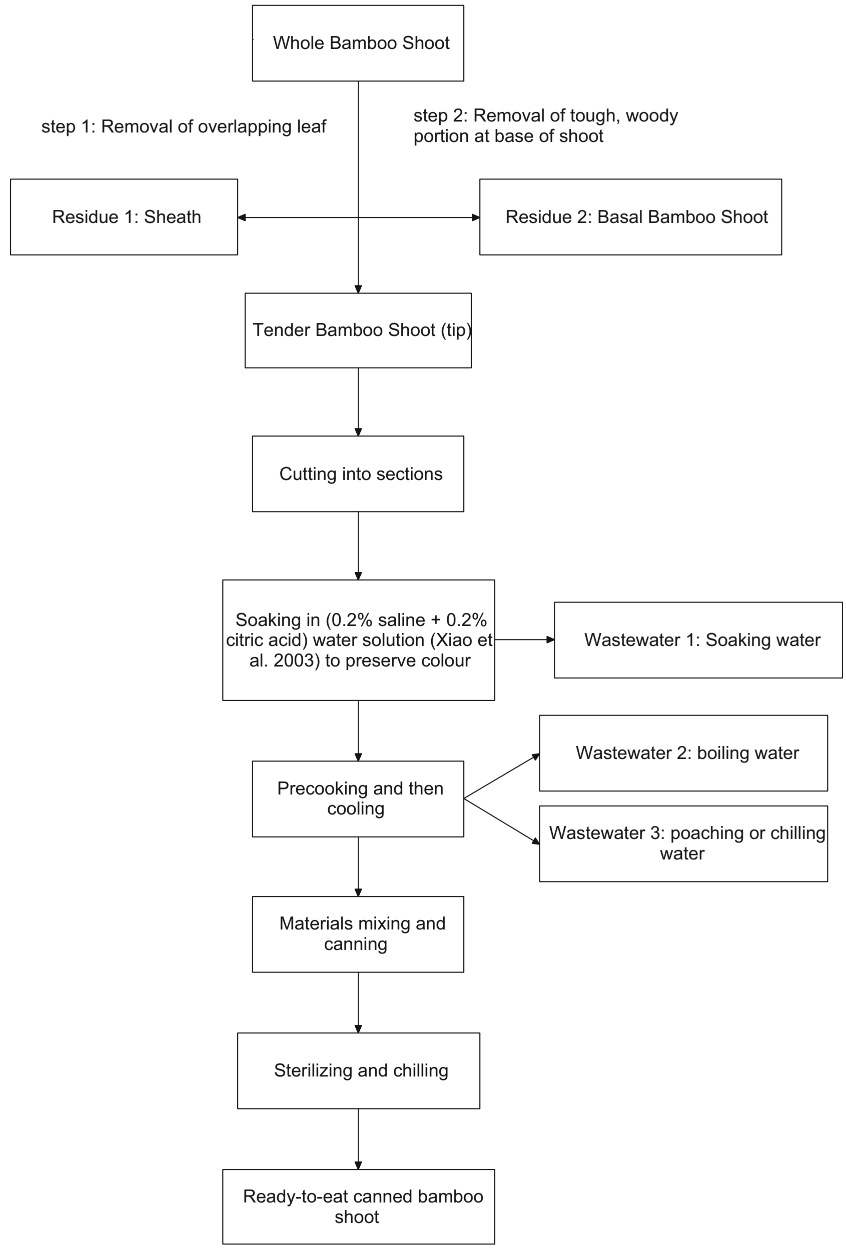

Fig. 2 Processing diagram for canned ready-to-eat bamboo shoots and the processing waste (BSPR and wastewater)

production of bamboo shoot and the high moisture content of BSPR (over 90%). However, ensilage can be introduced to preserve BSPR for year-round use (Jia et al. 2011), where the ensilage is a product of fermentation. Under anaerobic conditions, lactic acid bacteria produce a large amount of acid, so that the silage has a pH of 3.8–4.2. The low pH inhibits all microbial activities including lactic acid bacteria, so as to achieve preservation of the feed (Qi 2013).

In a study involving a rabbit feeding trial, the apparent digestibility of crude protein, crude fiber, dry matter, and organic matter was shown to reach 70.72, 25.67, 85.26, and 87.14%, respectively, indicating that BSPR ensilage can be used as a rabbit feed that is easily digested and an excellent fiber source (Wang and Wang 2012). The use of BSPR ensilage as an animal feed is valuable to farmers for maintaining livestock, and can also reduce the problem of environmental pollution caused by the uncontrolled decomposition of BSPR (Zeng and Yue 2015a).

Composition of BSPR and Bamboo Shoots

The common methods currently used for managing BSPR have problems such as environmental pollution, labor-intensive production, and low added value. Hence, it is necessary to find better methods for utilizing BSPR. As bamboo shoots are known to be rich in nutritional and bioactive compounds, there is potential for using the BSPR as a source of extractable compounds to create higher-value products such as functional food ingredients and health supplements. In this section, components from proximate analysis of bamboo shoots are discussed in comparison to BSPR; this is followed by a discussion of the bioactive compounds and toxins detected in the bamboo shoots and BSPR.

Proximate Nutrients

BSPR consisting of the sheath and basal area of the bamboo shoot contains similar nutrients as the tender shoot (Chen 2014a). Bamboo shoots have high nutritional value, and are rich in proteins, amino acids, mineral elements, vitamins, hemicellulose, lignin, dietary fiber, and a variety of bioactive ingredients. Although the proximate analysis of bamboo shoots has been reported for a variety of species, limited data are available for BSPR. Therefore, in this review, the proximate data for bamboo shoots and BSPR from selected studies are summarized in Table 1 for comparison. In general, the crude fat and total carbohydrate contents are similar for the different bamboo shoot parts in the same species; however, basal bamboo shoots and sheaths have much more crude fiber than the tip, whereas the tip has the highest protein content, followed by the basal bamboo shoot and the sheath, respectively. In the following sections, the proximate components in bamboo shoots and residues are further discussed.

Proteins

As indicated in Table 1, bamboo shoots are a good source of proteins (Lu 2007). In the study by Xu et al. (2005), the protein and amino acid content for bamboo shoots from nine different species were determined. Their results showed that the protein content of bamboo shoots ranged from 19.01 to 35.10 g/100 g dry weight (DW) and the total amino acid content ranged from 8.22 to 28.03 g/100 g DW. This is quite similar to the findings of Lu (2007), but higher than what was found by Lv (2013). The wide range of results can be due to the different bamboo species but also to the age, cultivation, and post-harvest processing conditions (Xu et al. 2005; Nirmala et al. 2007; Zheng et al. 2013; Pandey and Ojha 2014). The proteins in the bamboo shoot consist of a diverse range of natural peptides, and are predominantly low molecular weight (20.10 to 15.50 kDa) histone-like proteins (Waikhom et al. 2015). They contain 18 amino acids, of which 30.33–42.53% of the total amino acid content are essential amino acids (EAA) that must be supplied by the diet (Wang et al. 2011; Xu et al. 2005). This is close to the EAA proportion of fish (44.80~45.92%), and is close to the EAA requirement of adults (Xu et al. 2005).

The basal part and sheath appear to have less protein in general than the tender bamboo shoot, as indicated in Table 1. Table 1 also shows the amino acid content of concentrated aqueous extract fractions (CAEF) from bamboo shoot processing wastewater (including boiled water, filled liquid, squeezed juice, etc.), which was around 21.32 g/100 g DW (Liu 2012), and that for purified aqueous extract fractions (PAEF) was 42.78 g/100 g DW (Liu et al. 2012). Thus, BSPR and bamboo shoot processing wastewater show promise as a rich source of protein by-products (Waikhom et al. 2015). In addition, peptides derived from bamboo have also exhibited inhibitory activity against angiotensin-converting enzyme (ACE), and could be utilized as a nutraceutical in hypertension management (Chen et al. 2012b). Bamboo shoots and residues also contain peroxidases, which exhibit a variety of functions, such as defense against infection and lignification (Hsu et al. 2012).

Lipids

As shown in Table 1, the lipid contents in both bamboo shoots and BSPR are low, ranging from 0.98 to 3.9% DW for the bamboo shoots and 2.8–3.4% DW for the basal and sheath parts (Lu 2007; Lv 2011; Lv 2013). Studies of bamboo shoot oil (BSO) extracted by supercritical CO_2 indicate that it is composed of 70.04% fatty acids (i.e., 53.97% unsaturated and 16.07% saturated fatty acids) and 28.74% sterols. The main fatty acids were linoleic acid (28.14%), linolenic acid (17.57%), palmitic acid (7.35%), and oleic acid (6.42%), while the main sterols were β-sitosterol (24.63%), campesterol (2.18%), and stigmasterol (1.16%) (Lu et al. 2010). Other small amounts of fatty acids were also found in the tender bamboo shoot, sheath, and basal shoot too, such as butanedioic acid and dodecanoic acid (Lu 2007). In general, different parts of the bamboo shoot have similar lipid composition, though some compounds such as linoleic acid, calendic acid, and sitosterin have been detected at higher quantities in the sheath than in the tender bamboo shoot (Lu 2007).

Carbohydrates

According to the evidence shown in Table 1, there is no significant difference in total carbohydrate content between tender bamboo shoot and BSPR in the same species, but there is some difference in the fiber content. Dietary fiber is one of the main components of bamboo shoot. It is a mixture of cellulose, hemicellulose, lignin, pectin, and soluble polysaccharides (Deng 2008). The content of crude fiber in bamboo shoots ranged from 8.20 to 37.07 g/100 g DW. In comparison, the crude fiber in BSPR ranged from 21.3 to 23.2 g/100 g DW (Lu 2007; Lv 2011), and the dietary fiber content of BSPR ranged from 53.7 to 77.0%, which varied with the species, parts of bamboo shoot, and extraction methods (Xie et al. 2000; Deng 2008; Cao 2014). Within the three parts of bamboo shoot, the sheath and basal portions have much more dietary fiber than tender bamboo shoot; thus, the BSPR could

Table 1 Proximate nutrients of bamboo shoots and BSPR (g/100 g DW)

Part of bamboo shoot		Content: Protein	Amino acids	Lipids	Total carbohydrates	Crude fiber	Species	Reference
Tender bamboo shoot		19.01–35.1	8.22–28.03				Group 1	Xu et al. 2005
		1.59–3.78		0.98–1.77	15.9–22.5	13.97–37.07	Group 2	Lv 2013
		24.5–29.6		2.7–3.9	28.5–30.4	8.2–19.3	Group 3	Lu 2007
Whole bamboo shoot	Sheath	8.8 ± 1.3		3.4 ± 0.7	36.2 ± 1.9	23.2 ± 1.6	*Phyllostachys pubescens*	Lu 2007
	Basal	19.5 ± 1.1		2.8 ± 0.5	37.9 ± 2.6	21.3 ± 1.4		
	Tip	27.8 ± 1.3		3.2 ± 0.6	31.3 ± 2.3	9.4 ± 1.1		
Basal bamboo shoot		21.71 ± 0.21		5.98 ± 0.59		19.24 ± 0.05	*P. pubescens*	Lv 2011
CAEF			21.32 ± 1.16				*P. pubescens*	Liu 2012
PAEF			42.78 ± 0.57				*P. pubescens*	Liu et al. 2012

Group 1: *Phyllostachys bambusoides*, *P. heteroclada*, *P. sulphurea*, *P. iridenscens*, *P. praecox*, *P. meyeri*, *P. pubescens*, *phypramiens*, and *P. praecox huangshanensis*. Group 2: *P. tianmuensis*, *P. pubescens*, and *P. praecox*. Group 3: *P. pubescens*, *P. violascens*, *Dendrocalamus latiflorus*, and *Pleioblastus amarus*

BSPR bamboo shoot processing residue, which consists of basal bamboo shoot and sheaths, *CAEF* concentrated aqueous extract fractions, including boiled water, filled liquid, and squeezed juice, *PAEF* purified aqueous extract fractions

be developed into healthy foods, food supplements, and ingredients (Li et al. 2010; Xu et al. 2013; Chen 2014b; Han and Jin 2015).

In terms of other carbohydrates, xylan is the main component of hemicellulose in the cell wall of many plants (including bamboo shoots), and can degrade to xylooligosaccharides and xylitol, which can be used in functional foods (Yu et al. 2012; Zhu et al. 2015). Sodium carboxymethyl cellulose, which could be used as food thickener and pharmaceutical excipient, can also be obtained from the fiber in bamboo shoots and its residues (Shi et al. 2013). Thus, these carbohydrates can extend the use of bamboo shoot residues for value-added applications.

Minerals and Vitamins

There have been some studies on the mineral content of bamboo shoots, but few that have focused on BSPR. Bamboo shoots are rich in minerals, especially phosphorus (685.3 mg/100 g DW), magnesium (200.9 mg/100 g DW), and calcium (102.9 mg/100 g DW) (Wang et al. 2011). When compared with 34 other common vegetables, the potassium (268 mg/100 g), zinc (0.59 mg/100 g), and manganese (0.5 mg/100 g) contents of bamboo shoots are high (ranked seventh, tenth, and fifth highest, respectively) (Li and Wu 2006). In comparison, the contents of phosphorus and calcium in BSPR are 1250 and 860 mg/100 g DW, respectively (Chen 2014a), which appear higher than in the bamboo shoot. These minerals are important for maintaining good health and have therapeutic value; for example, calcium is known to play a part in muscle contraction and is a key factor for strong bones (Pandey and Ojha 2014).

Only a few studies have measured the vitamin content in bamboo shoots, with most of them focused on vitamin C (ascorbic acid) and vitamin E. One study reported that the vitamin C content extracted with methanol and water from *Phyllostachys* (*P.*) *pubescens* and *P. nigra* ranged between 136.3 and 231.8 mg/100 g DW (Park and Jhon 2010). To the best of our knowledge, there are no published data available on the vitamin content of BSPR.

Bioactive Compounds

Some common bioactive compounds that have been detected in bamboo shoots and BSPR are summarized in Table 2, including phytosterols, phenolic acids, flavonoids, triterpenes, and polysaccharides (Lu 2007; Yang and Huang 2009; Lv 2011; Liu 2012; Liu et al. 2012; Lv 2013). It is evident that there are significant differences in the polysaccharide content of the tender bamboo shoot, sheath, and basal parts, but not in the other bioactive compounds. Bamboo shoot sheath has the lowest polysaccharide content, but has the highest content of phytosterols, phenolic acids, flavonoids, and triterpene,

Table 2 Bioactive components of bamboo shoot and BSPR (mg/100 g, DW)

Part of bamboo shoot		Content				Species	Reference
		Phytosterols	Phenolic compounds		Polysaccharides		
			Phenolic acids (mg HBAE/100 g DW)	Flavonoids (mg RE/100 g DW)			
Tender bamboo shoot				580–830		Group 2	Lv 2013
		251.4–279.5	25.2–30.6	19.8–28.6	231.7–253.2	Group 3	Lu 2007
				279–1348		Group 4	Yang and Huang 2009
Whole bamboo shoot	Sheath	292.3 ± 15.8	30.8 ± 2.5	26.6 ± 1.8	182.1.3 ± 11.8	*Phyllostachys pubescens*	Lu 2007
	Basal	281.5 ± 12.4	28.2 ± 2.1	24.3 ± 2.0	238.3 ± 13.7		
	Tip	257.9 ± 13.1	21.4 ± 1.7	18.2 ± 1.4	293.8 ± 14.2		
Basal bamboo shoot		365.52 ± 1.25		24.71 ± 1.83		*P. pubescens*	Lv 2011
Sheath				420–910		Group 2	Lv 2013
CAEF			4780 ± 240 (mg GAE/100 g DW)	1410 ± 120		*P. pubescens*	Liu 2012
PAEF			10,910 ± 980 (mg GAE/100 g DW)	5070 ± 470		*P. pubescens*	Liu et al. 2012

Group 2: *P. tianmuensis*, *P. pubescens*, and *P. praecox*. Group 3: *P. pubescens*, *P. violascens*, *Dendrocalamus latiflorus*, and *Pleioblastus amarus*, Group 4: *Pleioblastus amarus*, *Pleioblastus juxianensis*, and *Pleioblastus maculatus*

BSPR bamboo shoot processing residue, which consists of basal bamboo shoot and sheaths, *CAEF* concentrated aqueous extract fractions, including boiled water, filled liquid, and squeezed juice, *PAEF* purified aqueous extract fractions, *HBAE* hydroxybenzoic acid equivalents, *GAE* gallic acid equivalents, *RE* rutin equivalents

whereas the tender bamboo shoot has the highest polysaccharide content and lowest content of the other compounds, and the basal bamboo shoot has medium levels of all the compounds. The following sections discuss the content of phytosterols, phenolic compounds, and polysaccharides in more detail.

Phytosterols

Phytosterols are bioactive components that are found in plants, and their presence in fresh or fermented bamboo shoots is very prominent (Lu et al. 2009; Nongdam and Tikendra 2014). The total phytosterol contents of bamboo shoot and BSPR are shown in Table 2. It ranged from 251.4 to 279.5 mg/100 g DW in bamboo shoots, and ranged from 281.5 to 365.5 mg/100 g DW in BSPR (Lu 2007; Lv 2011). This indicates that bamboo shoots are a phytosterol-rich food, and as such, beneficial for health, with BSPR having a higher phytosterol content than bamboo shoot. As pointed in the study of Lu et al. (2009), the total sterol content in bamboo shoots was affected by genetic variability, the part of the plant tested, and the harvest season. Among all the tested samples, which were from four species of bamboo shoots, six parts (shoot bodies and sheath), and three harvest seasons (spring, summer, and winter) of *P. pubescens*, the sheaths from spring shoot possessed the highest level of total sterols (321.8 mg/100 g DW). Therefore, bamboo shoot sheaths could be regarded as a potential source of dietary phytosterols (Lu et al. 2009; Nongdam and Tikendra 2014).

Phenolic Compounds: Phenolic Acids and Flavonoids

Phenolic compounds exhibit antioxidant activity, and could prevent the effects of free radicals and reactive oxygen species, which are strongly associated with aging, carcinogenesis, and cardiovascular disease (Moskovitz et al. 2002; Nemenyi et al. 2015). Phenolic acids and flavonoids are the two main polyphenolic classes in the bamboo species (Jiang 2008; Park and Jhon 2010; Hoyweghen et al. 2012).

As shown in Table 2, the total phenolic acids of bamboo shoot ranged from 21.4 to 30.6 mg HBAE/100 g DW (hydroxybenzoic acid equivalents, HBAE) with different species, while the contents of BSPR ranged from 28.2 to 30.8 mg HBAE/100 g DW (Lu 2007). There does not appear to be much difference between the total phenolic acid contents of the bamboo shoot and BSPR. However, when comparing the results of the different bamboo shoot parts for *P. pubescens*, it is evident that basal bamboo shoot and sheath have more phenolic acids than the tender bamboo shoot (Lu 2007). Table 2 also reveals that bamboo shoot processing wastewater has high phenolic acids content, up to 4780 mg GAE/100 g DW (gallic acid equivalents, GAE) in the CAEF and 10,910 mg GAE/100 g DW in the PAEF (Liu 2012; Liu et al. 2012). The flavonoid contents of the bamboo shoot ranged from 279 to 1348 mg RE/100 g DW (rutin equivalents, RE) (Yang and Huang 2009; Lv 2013); it is much higher than the result obtained by Lu's study (Lu 2007), where the flavonoid contents ranged from 19.8 to 28.6 mg RE/100 g DW. The study by Lu (2007) also shows that sheath has the highest flavonoid content when compared with the basal bamboo shoot and tender bamboo shoot, while the tender bamboo shoot has the lowest flavonoid content. As shown in Table 2, CAEF and PAEF from bamboo processing wastewater also have high flavonoid content (Liu 2012; Liu et al. 2012).

There are additional studies focused on the composition of phenolic acids and flavonoids in bamboo shoots. Analysis of edible bamboo shoots by HPLC identified eight phenolic acids in the extract, with the most abundant compounds being catechin, *p*-hydroxybenzoic acid, chlorogenic acid, and syringic acid (Park and Jhon 2010), as depicted in Fig. 3. While the most common forms of flavonoids in the bamboo shoots are flavones and flavonols, other compounds that are also present can include flavanones, isoflavones, chalcones, and anthocyanins (Yang and Huang 2009), as shown in Fig. 4. The antioxidant ability of flavonoids is associated with the substituent groups of A and B rings and the unsaturated bond within the C ring (Fig. 4). The more phenolic hydroxyl groups that are present, the stronger the antioxidant capacity of the flavonoids (Liu 2012). To the best of our knowledge, data on the composition of phenolic acids and flavonoids in BSPR are not available.

Polysaccharides

Polysaccharides in bamboo shoots are thought to have antioxidant, anticancer, and immunomodulation activities (Lu 2007; Sun et al. 2016). Bamboo shoot crude polysaccharides extracted from different species and different parts of the plant yielded from 2.19 to 8.47% (Chen et al. 2012a; Wu et al. 2015; Zhang et al. 2015; Zheng et al. 2015). Recently, the water-soluble polysaccharides in *P. praecox* shoots extracted with hot water and purified by chromatography were identified as heteropolysaccharide-protein complexes (He et al. 2016). In another study, three kinds of polysaccharides isolated by Wu et al. (2015) were all found to contain glycopeptide bonds. The tender bamboo shoot has more polysaccharides than the basal bamboo shoot and sheaths (Lu 2007), which is quite different from the distribution of dietary fiber. Thus, BSPR would be better utilized as a source of dietary fiber than polysaccharides for value-added products.

Cyanogenic Glycosides

As discussed previously, bamboo shoots and its processing residues are rich in various macronutrients and micronutrients and bioactive compounds that are beneficial to human health. However, they also contain cyanogenic glycosides, namely, taxiphyllin, which may pose serious health problems, and should not be ignored (Singhal et al. 2013; Nongdam and Tikendra 2014). Cyanide poisoning from cyanogenic glycosides commonly occurs after ingestion, and can also occur by

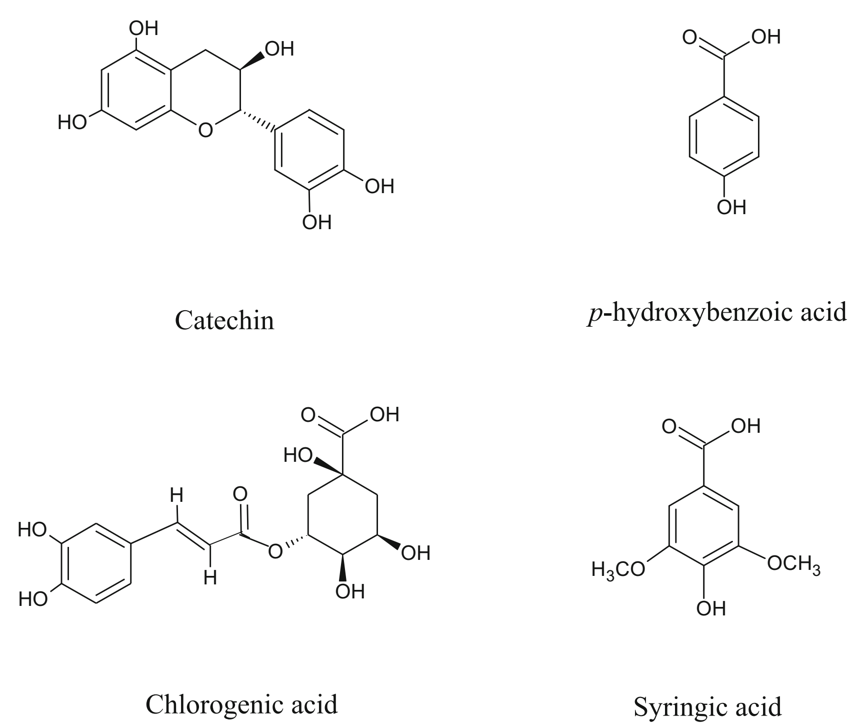

Fig. 3 Examples of major phenolic acids in bamboo shoots

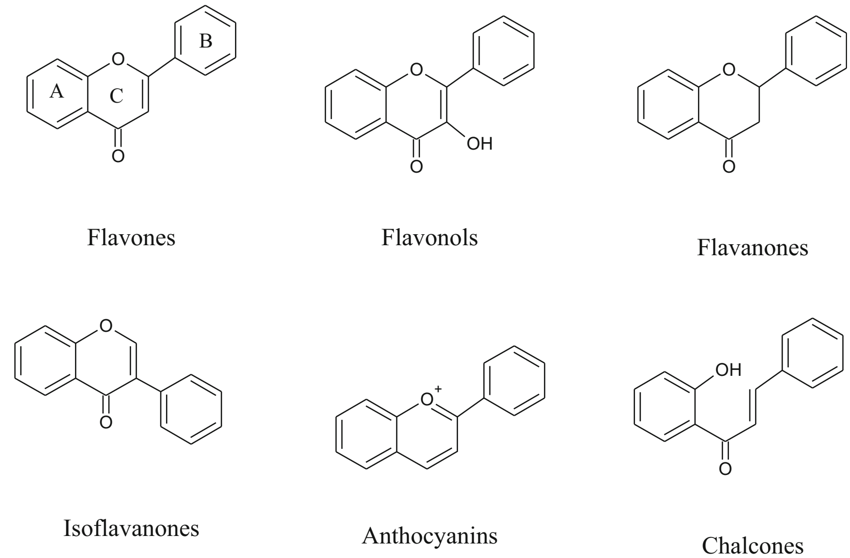

Fig. 4 Classes of flavonoids in bamboo shoots

inhalation, or absorption through the skin and eyes. Hydrogen cyanide (HCN) gas is produced by hydrolysis of the cyanogenic glycosides, and has caused fatalities associated with special bamboo shoot processing, e.g., pickling (Sang-A-Gad et al. 2011; Bal et al. 2012).

The cyanogenic content ranges from 39 to 434 mg/kg in fresh bamboo shoots (Sang-A-Gad et al. 2011), and varies according to the different parts of the shoots that are tested, the bamboo species, geographical and climatic conditions, and analysis methods used (Satya et al. 2010; Bal et al. 2012; Waikhom et al. 2013). Previous research has suggested that the total cyanogenic content (TCC) of bamboo shoots collected from lower altitudes was higher than that from high altitudes, and it decreased from the tip to the middle, and then to the basal area (Satya et al. 2010; Waikhom et al. 2013). As reported by Zeng and Yue (2015b), bamboo shoot sheaths may have the lowest TCC, with an average value of 15.39 mg/kg FW. The acute lethal dose of hydrogen cyanide was reported as 0.5–3.5 mg/kg body weight for humans (Food Standards Australia New Zealand 2004); thus, approximately 30–210 mg of free cyanide from bamboo shoot or its residue constitutes a lethal dose for an adult with 60 kg weight.

The use of bamboo shoot sheaths as an animal feedstuff should be treated with caution, as animal poisoning and death could occur if the cyanogenic content is too high, which would result in significant economic losses (Zeng et al. 2016). It is very evident that the presence of cyanogenic glycosides in bamboo shoots and its processing residues should be eliminated appropriately and not be neglected. Food processing procedures such as chopping, soaking, boiling, drying, fermentation, and storage could reduce the levels of hydrogen cyanide (Satya et al. 2010; Bal et al. 2012; Singhal et al. 2013; Pandey and Ojha 2014), as these processes will allow time for decomposing cyanogenic glycosides to free cyanide, which would then dissipate out of the food matrix (New Zealand Food Safety Authority n.d.).

Utilization Potential of BSPR

Studies have shown that BSPR could be used as fertilizer and animal feed. Basal bamboo shoots and bamboo sheaths fermented with rice polishings, corn flour, and other nutrient additives have been found to produce a good fertilizer for mushrooms such as *Agaricus bisporus*, cap fungus, and glossy ganoderma (Lv 2008; Chen 2014a). This application can also be extended to other greenhouse vegetables, flowers, and plants. Studies have shown that both fermented BSPR and the substrate remaining after mushroom harvest are rich in protein, minerals, crude fiber, and bioactive ingredients (Wang and Wang 2012; Qi 2013; Zeng and Yue 2015a; Liang et al. 2016). Thus, they could be processed as feed additives or as a functional feed, which might enhance the immune system and lower the cholesterol levels of livestock and poultry (Chi et al. 2007; Lin et al. 2004).

Recent research on the nutrients and bioactive compounds of bamboo shoots and its processing wastes has led to the emergence of new avenues for utilization in the food industry, including use in functional foods and as health-promoting nutraceuticals. The review articles published by Choudhury et al. (2012) and Chongtham et al. (2011) include examples where juvenile (tender) bamboo shoots are used for food applications, such as a functional ingredient to a variety of food products. These include the addition of bamboo fiber to decrease crumbling in bakery products and to enrich the fiber content for improved health benefits, the improvement of viscosity and mouthfeel for dairy products such as yoghurt and other health beverages, and the increased water retention capacity for meat and aquatic products.

Given the current food applications of the tender bamboo shoots, the associated processing residues (BSPR) have great potential as a dietary fiber source for the food industry, where the bamboo shoot sheaths and basal bamboo shoots could be processed into functional foods which might have beneficial effects on lipid profile, bowel function, hypertension, diabetes, and obesity (Zhang 2009; Chandramouli and Viswanath 2012; Liu 2012; Chen 2014b; Zheng et al. 2016). BSPRs are also rich in phenolic compounds and phytosterols. These components have very important physiological and pharmacological activities, such as antioxidation, antiaging, antifatigue, antibacterial, anti-inflammatory, and antihyperlipidemia (Lu 2007; Singhal et al. 2013; Nirmala et al. 2014; Nongdam and Tikendra 2014; Nemenyi et al. 2015).

Xylan, xylooligosaccharide, xylitol, and sodium carboxymethyl cellulose extracted from bamboo shoot sheaths could also be used as food additives and functional food ingredients, and the by-products can be used to produce polyols which are a form of biomass energy (Ye et al. 2014). Bamboo sheaths are also a potential source of peroxidase for bioanalytical or biotechnological applications, such as enzymatic reagents for food analysis, clinical diagnosis, and biotransformation of various chemicals (Jiang 2008; Hsu et al. 2012).

In addition, bamboo shoot processing wastewater contains peptides and amino acids and possesses angiotensin-converting enzyme (ACE) inhibitory activity; therefore, they have potential to be used as a protein supplement, seasoning agent, and functional beverage, and also as a source of nutraceuticals for the prevention of hypertension and attenuation of oxidative stress (Huang and Lu 2008; Chen et al. 2012a, b; Liu 2012; Liu et al. 2013; Waikhom et al. 2015).

Discussion and Future Work

Although there are many potential applications for BSPR, a number of limitations exist. Firstly, most of the research on the processing and utilization of BSPR residue has been conducted from different angles, rather than using a systemic approach. Thus, extraction of particular compounds is typically done without considering the further use of the remaining residue. In this way, it is not possible to maximize the value of BSPR. Rather, a biorefinery approach (Maity 2015) should be taken for the BSPR, where the BSPR is treated as the raw material for multiple products that arise from sequential processing and where the waste from one process becomes the feed material for subsequent products. Secondly, fresh BSPR is

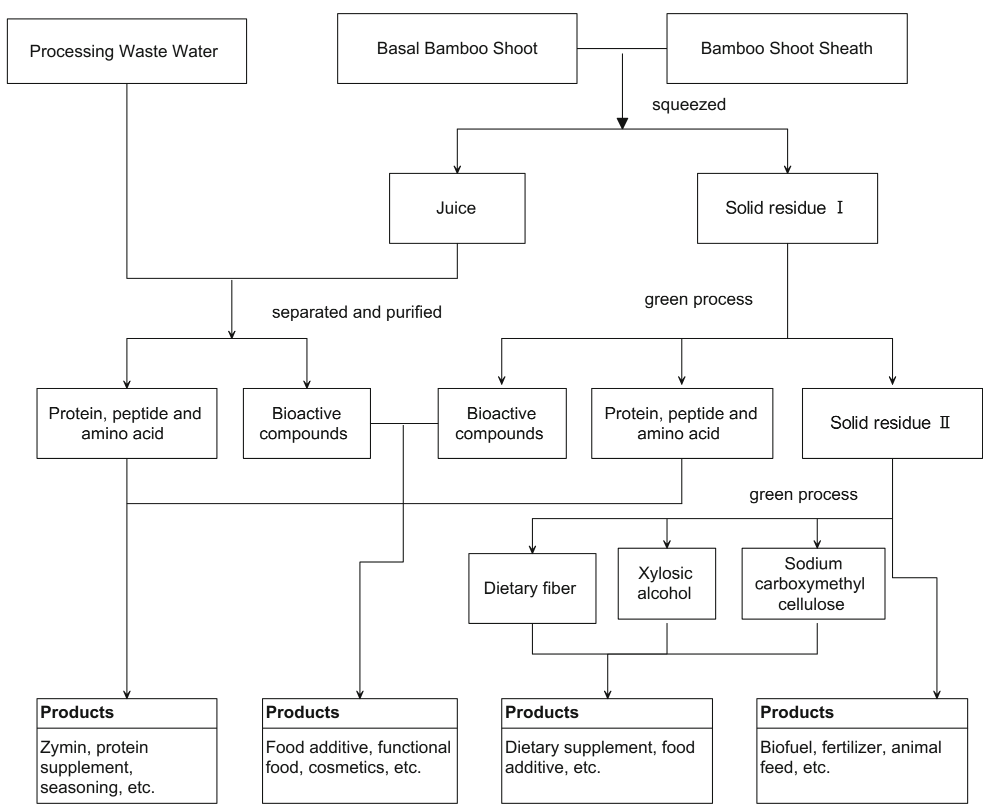

Fig. 5 Proposed flow chart for a biorefinery approach to the development of value-added products from waste bamboo shoot processing residue (BSPR) and processing wastewater

susceptible to degradation, as it has high moisture content and is harvested in a season which is typically wet and hot. However, there are few reported studies on the preservation of BSPR, although this is a key consideration which would affect the reuse of the processing residues. Thirdly, there are few reported studies on the cyanogenic content of BSPR, which is important considering that BSPR could be used as an additional nutritional source and could threaten the safety of human beings or animals if not properly addressed. Fourthly, the microbiological safety and presence of contaminants in the fresh BSPR and wastewater must be considered when defining a process for the production of food ingredients or for the extraction of bioactives to be used in food and food supplements.

Efforts need to be made in developing methods to utilize surplus BSPR for functional food products, nutraceuticals, and cosmetics. A systemic approach for maximizing the utilization of BSPR through a biorefinery approach should be investigated. For example, the juice squeezed from basal bamboo shoots and the bamboo shoot processing water could be used for protein products, such as zymin, protein supplements, and seasoning agents (Jiang 2008; Chen et al. 2012a, b). Then the remaining solids after juicing could be further extracted with a green solvent (e.g., deep eutectic solvent) for the bioactive compounds, like phenolics and phytosterols (López et al. 2015; Duan et al. 2016). The extracts could be used for food additives, functional foods, and cosmetics. Finally, the residual solids could be further used to obtain dietary fibers, xylosic alcohol, sodium carboxymethyl cellulose, biofuel, fertilizer, or animal feed. The possible systemic development of BSPR is exhibited in Fig. 5.

The preservation of fresh BSPR is important too. Current preservation methods for bamboo shoots include low temperature, modified atmosphere preservation, vacuum method, ozone method, and film preservation (Chen et al. 2011; Yang and Liu 2011; Lin et al. 2012; Song et al. 2013). Whether these methods are suitable for BSPR, given the relative high costs involved with each preservation technique, should be assessed. In addition, the practicalities of accommodating the quantities of BSPR produced by industrial processing are an important consideration, especially as the harvesting and processing season is fairly short. The removal of taxiphyllin from bamboo has been investigated, and studies have shown that it can be easily removed by various processing methods, such as boiling, soaking, drying, and fermentation. However, further research should be conducted on innovative ways to eliminate the toxic cyanogenic material without disturbing the nutrients and bioactive substrates present in the BSPR.

Conclusion

Bamboo shoot processing residues (BSPRs) are produced in huge quantities and can be a significant environmental burden. Utilization of BSPR for high-value products has much potential, as it is rich in proteins, amino acids, carbohydrates, minerals, vitamins, and bioactive compounds, such as phenolics, phytosterols, and dietary fibers, which play a potential role in providing protection against many chronic and degenerative diseases, such as cardiovascular disease and diabetes. A systematic biorefinery approach is needed to maximize the value from BSPR. Although there are some limitations and issues that must be addressed before BSPR can be properly utilized, there is much promise for the development of BSPR into value-added products.

Acknowledgments

Financial support through the Education Department of Fujian Province, China, and the Natural Sciences and Engineering Research Council of Canada (NSERC) is gratefully acknowledged.

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