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MINI REVIEW

Exploitation of plant-derived food waste for valuable products using bioprocesses: a narrative review

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Abstract

Globally, a million tons of plant-derived food waste are generated annually from various cultivation activities and agro-industrial manufacturing. When food waste decomposes, it releases methane gas that causes global warming. The exploitation of food wastes for valuable products provides an alternative approach to environmental protection. This paper aimed to review the exploitation of plant-derived food waste for valuable products and to evaluate different bioprocesses for optimum yields of the valuable products. This review study was conducted by using PubMed, ScienceDirect, and NCBI databases. A total of 169 publications were screened and 43 papers of high relevance were selected. Cereal wastes such as wheat straw, rice bran, root and tuber waste, and fruits and vegetable pomace contribute the most amounts to the total food waste worldwide. These wastes serve as renewable sources for bioactive production. Various fermentation processes involving enzymes, yeast, or bacteria were used to convert food waste into valuable products such as phenolics, flavonoids, dietary fibre, carotenoids, lignocellulose, phytosterols, tocotrienols, coumaric acid, oryzanol, citrulline, vitamins, and essential amino acids. Several bioprocesses and the optimization conditions for the maximum yield of valuable products were highlighted. In the production of xylitol from corn cobs using yeast (*Debaryomyces hansenii*), a higher yield (0.216 g xylitol/g xylose) was obtained through enzyme hydrolysate fermentation compared to acid hydrolysate fermentation (0.100 g xylitol/g xylose). In the production of fungal chitosan using solid-state fermentation, the yield was 3 folds higher (34.4 g/kg substrate) for soybean meals substrate than potato peels substrate (10.8 g/kg substrate). Plant-derived food waste serves as a renewable substrate for the production of health-promoting bioactive compounds through the optimization of various bioprocesses. The exploitation of plant-derived food waste for high-value products has significant implications for environmental impact, public health, and economic gain.

1. Introduction

Worldwide, cultivation activities and agro-industrial manufacturing generate a vast amount of food loss and waste every year. According to FAO (2012), approximately 1.3 billion tonnes of food are lost or wasted globally along the food supply chain, representing one-third of the edible portion of the total volume of food that is produced for human consumption. The rising global population and changing diet habits, result in increased demand for plant-based food production and thus a naturally associated accentuation in increased plant-derived food wastes (PFW). PFW signifies the larger portion in the whole food life cycle, which accounted for 63% as compared with animal-derived waste (Pfaltzgraff *et al*., 2013). Paritosh *et al.* (2017) reported that total food wastes from various food communities, in descending order of amounts, were generated around the world (Figure 1), of which the statistical data are obtained from the FAO Statistical Yearbook 2013 (FAO, 2013). A large portion of PFW generated annually is underutilized, untreated, and undisposed properly. Consequently, PFW has been associated with significant global concerns including public health concerns, world hunger due to food insecurity, economic difficulty, failure to achieve sustainable development goals as well as severe environmental issues such as greenhouse gas emissions. The exploitation of PFW by recovering or recycling PFW into valuable products serves as part of the integrated efforts to reduce global food waste. In this

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context, the main objective of the literature review is to review the exploitation of plant-derived food wastes for valuable products and to evaluate different bioprocesses, namely submerged fermentation, solid-state fermentation, and immobilized cell fermentation, for optimum yields of the valuable products.

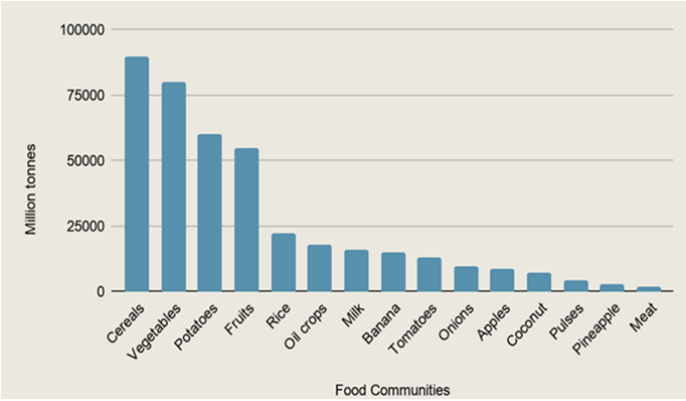

Figure 1. Bar chart of total food wastes from various food communities around the world. (Source: Paritosh *et al*., 2017)

2. Methodology

This narrative review required a comprehensive literature search for capturing scientific papers with high relevance to the topic. This review involves a five-step process.

2.1 Determination of the scope of research questions

The first key step of narrative review required to define the research questions and scope. The following are the research questions guided for this review: (i) What are the valuable products that can be recovered from plant-derived food wastes? (ii) What are the bioprocesses used for converting plant-derived food wastes into valuable products? (iii) How are the optimization of bioprocesses conditions or parameters conducted for maximum production yield?

2.2 Identification of relevant studies

This review was conducted by searching studies from PubMed, ScienceDirect, and NCBI electronic databases, published throughout 2010 - 2021. Several keywords including plant-derived food wastes, renewable sources, bioactive compounds, bioprocesses, and valuable products were chosen as search terms for identifying the relevant publications. The database searches were restricted to the English language only.

2.3 Selection of study

A flowchart of the study selection process from identification to final inclusion is represented in Figure 2. The selection of study in this narrative review was executed by inclusion and exclusion criteria based on different aspects. Inclusion criteria covered the publications were in English, published in PubMed, ScienceDirect, and NCBI and the research papers must be within the year range of 2010-2021. Studies and research on animal-derived food wastes were excluded from this review. Duplicate articles and papers without the full text were also excluded. A total of 169 publications were screened carefully for multiple rounds and only 43 papers of high relevance that met all inclusion criteria were selected for this review.

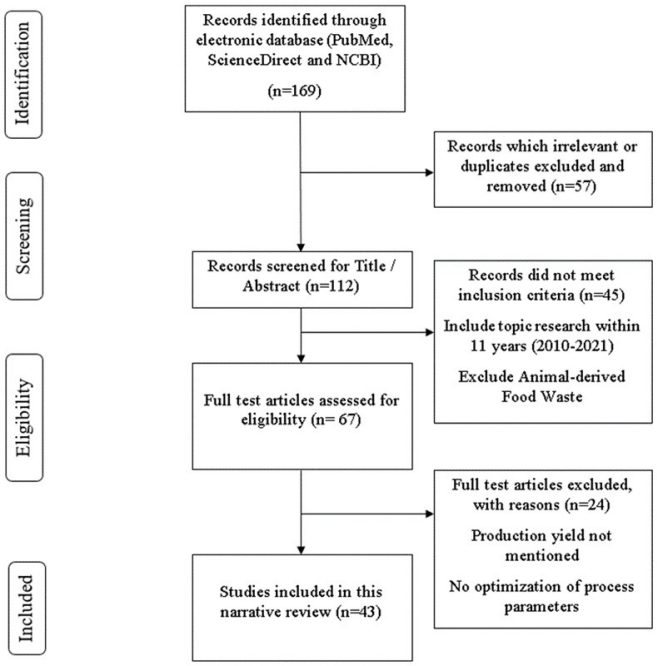

Figure 2. Flowchart of study selection process from identification to final inclusion.

2.4 Data extraction

In this step, collecting or extracting applicable information from the selected papers and making a decision on the selection of data that is relevant to the problem of interest.

2.5 Analysis, summary, and documentation of findings

In the final step of the narrative review, the findings and data extracted from the selected publications which met all the inclusion criteria were analyzed, summarized, evaluated, organized, and documented in the results for achieving the objectives of this literature review as well as providing sufficient information and answering the scope of research questions defined in the first key step.

3. Results and discussion

A diversity of plant-derived food wastes including cereals wastes, root and tuber wastes, and fruits and vegetable wastes represent excellent sources of high-value bioactive compounds such as phenolics, flavonoids, dietary fibre, carotenoids, lignocellulose, phytosterols, tocotrienols, coumaric acid, oryzanol,

citrulline, vitamins, and essential amino acids. Table 1 summarizes the recovery of target bioactive components from selected sources of plant-derived food wastes. The main bioprocesses used for converting plant-derived food waste into valuable products were submerged fermentation, the solid-state fermentation, and immobilized cell fermentation. The advantages and limitations of the bioprocesses were evaluated based on cost and time efficacy, productivity, operation complexity, and problems encountered (Table 2). Table 3 shows the conversion of plant-derived food wastes into valuable products using different types of substrates, microorganisms, and fermentation methods. These factors as well as optimization of bioprocess conditions significantly affect the production yields.

3.1 Antioxidants

Rashid *et al*. (2015) reported that fermented rice bran is responsible for improving the production of bioactives such as phenolic acids, ɣ-oryzanol, and α- tocopherol from rice bran and enhancing its antioxidant activity. These bioactive compounds are produced by the action

Table 1. Summary of selected sources of plant-derived food wastes and the target bioactive components

Plant-derived Food Wastes Origin	Selected Sources	Target Bioactive Components	References
Cereal	Wheat bran	Lignans; Dietary fiber (β-glucans, arabinoxylan); Phenolic acid; Flavonoids; Vitamin E	Stevenson *et al.* (2012)
	Wheat straw	Lignocellulosic materials (cellulose, hemicellulose, lignin); policosanols; phytosterols	Dunford and Edwards (2010)
	Rice bran	γ-oryzanol; Tocopherols, tocotrienols; Arabinoxylan; Albumin and globulin	Sardarodiyan and Salehi (2016); Adebiyi *et al.* (2008)
	Paddy straw	Lignocellulosic materials; ferulic acid; *p*-coumaric acid; caffeic acid	Freitas (González-Martínez and Chiralt (2020)
	Barley bran	β-glucans	Din *et al.* (2018)
	Brewer's spent grain	Amino acids (glutamic acid, histidine, lysine); Vitamins (niacin, choline); Ferulic acid; *p*-coumaric acid	Bianco *et al.* (2020)
	Corn cob	Hemicellulose (xylan); Flavonoids (tricin and kaempferol); *p*-coumaric acid	Arumugam and Anandakumar (2016); Ashour *et al.* (2013)
Root and tuber	Potato peel	Carbohydrates and polyphenol and phenolic acids (chlorogenic acid)	Javed *et al.* (2019)
	Sugarcane bagasse	Lignocellulosic biomass	Guilherme *et al.* (2015)
	Peanut skin	Proanthocyanidins; Flavonoid glycosides	Dean (2020)
Fruits and vegetables	Apple pomace	Pectin; Citric acid	Perussello *et al.* (2017)
	Tomato waste	Carotenes (lycopene, β-carotene); Phenolic compounds; Vitamins (ascorbic acid, vitamin A)	Domínguez *et al.* (2020)
	Pomegranate peel	Phenolic acid (gallic acid, ferulic acid); Tannins (ellagitannins, punicalagin); Flavonoids	Chen *et al.* (2020)
	Watermelon rind	Pectin; Dietary fiber; Citrulline	Naknaen *et al.* (2016); Tarazona-Diaz *et al*. (2011); Rimando and Perkins-Veazie (2005)

Table 2. Evaluation of bioprocesses in terms of advantages and limitations

Methods	Advantages	Limitations	Reference
Submerged Fermentation	• Short fermentation period • Low cost • Commercially available in large scale	• Substrate need to be replaced constantly • More effluent generation • Complex fermentation operation • Rheological problem	Aryal (2019a); Doriya *et al*. (2016)
Solid-state fermentation	• Reduction of energy requirements for sterilization • Reduced downstream processing • High yield and product activity • Easy preparation of substrate • Low cost of production process	• Substrate with low moisture content is preferred • Large-scale inoculums are difficult to control process parameters. • Problem with heat build-up	Sadh *et al.* (2018); Aryal (2019b); Doriya *et al*. (2016)
Immobilized Cell Fermentation	• High product yield and cell productivity • Cell washout can be avoided • The lag phase occurs in a conventional batch fermentation is eliminated • Reuse of cells as cell regeneration	• Product overgrowth • Modification of the end product by other enzymes • Diffusional barriers hindering substrate access	Zhu (2007); Kosseva (2010); Eş *et al.* (2015)

of three lactic acid bacteria (LAB), namely *Pediococcus acidilactici*, *Pediococcus pentoseous,* and *Lactococcus lactis* and using rice bran as substrate in solid-state fermentation. Rice bran fermented with *P. acidilactici* showed the highest yield of antioxidants: ɣ-oryzanol (1148.38 µg/mL), α-tocopherol (182.37 µg/mL), ferulic acids (8.56 µg/mL), total phenolic content (246 µg/mL) after 48 hrs of incubation as compared to the fermented rice bran with the other two LAB and unfermented rice bran. However, the main issue that limits the exploitation of these bioactive compounds is their insolubility, due to their chemical structure in bound form. The major bound phenolic acids, such as ferulic acids are naturally present in the rice bran and their concentration increased after 48 hrs of fermentation (Rashid *et al.*, 2015). This is because of the enzyme ferulic acid esterase produced by *P. acidilactici* during fermentation, which can break the ester links and thus improve the ferulic acid through the release of monomers of phenolic acids (Anastasia *et al*., 2012). During the fermentation process, the β-glucosidase enzyme and esterases synthesized by *P. acidilactici* potentially enhance the polyphenol content and thus significantly increase the bioavailability of polyphenol. Besides, the improved antioxidant activity as indicated by the increased DPPH radical scavenging activity of microbial fermented rice bran is associated with the bioactive compounds in rice bran. The DPPH radical scavenging activity in unfermented rice bran (66.2%) increased to 82.6% after microbial fermentation of rice bran with *P. acidilactici* (Rashid *et al*., 2015). This study suggested that the application of LAB fermentation in rice bran improved its free radical scavenging activity.

Watermelon rind has been reported as a good source of bioactive compounds. A relatively high amount of citrulline content (24.7 mg/g dry weight) in watermelon rind was reported by Rimando and Perkins-Veazie (2005). The freeze-dried samples of watermelon rind were extracted with 6 M HCL in a sonicating bath for 20 mins. The samples were heated at 145^{o}C for 4 hrs, cooled to room temperature, filtered and washed twice with 6 M HCL. The filtrates were combined and dried in a Speedvac. Citrulline was then analyzed by gas chromatography-mass spectrometry. The presence of L-citrulline, vitamins A and C, flavonoids, phenolic compounds especially 4-hydroxy benzoic acid and vanillin, saponins, terpenoids, and alkaloids in the watermelon rind contributed to its strong antioxidant properties and protection against free radical damage (Duran *et al*., 2017; Kumar *et al*., 2018).

3.2 Natural alternative sweetener (xylitol)

Mardawati *et al*. (2018) studied the effect of acid hydrolysis and enzymatic hydrolysis on the production of fermentation product (xylitol) from corn cob hydrolysate using yeast (*Debaryomyces hansenii*). Their results showed that enzymatic hydrolysis of corn cobs significantly increased the growth of *D. hansenii* during fermentation. The enzymatic hydrolysate fermentation showed a faster specific growth rate (0.039/h) than that of acid hydrolysate fermentation (0.0056/h) resulting in

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Table 3. Conversion of plant-derived food wastes into valuable products using appropriate microorganisms, bioprocesses and their production yields

Valuable Products	Renewable Sources/ Substrates Used	Microorganisms	Methods	Product Yield	References
Antioxidant	Rice bran	*Pediococcus acidilactici*	Solid state fermentation	Total Phenolic Content: 246 µg gallic acid /mL samples	Rashid *et al.* (2015)
Total Dietary Fiber	Wheat bran	*Lactobacillus bulgaricus* and *Streptococcus thermophilus*	Solid state fermentation	55.50 g/100 g	Zhao *et al.* (2017)
Xylitol	Corn cobs	*Debaryomyces hansenii*	Acid hydrolysis followed by Submerged batch fermentation	0.100 g-xylitol/g-xylose.	Mardawati *et al.* (2018)
Xylitol	Corn cobs	*Debaryomyces hansenii*	Enzymatic hydrolysis followed by Submerged batch fermentation	0.216 g-xylitol/g-xylose	Mardawati *et al.* (2018)
Natural Red Pigment	Brewer's Spent Grain	*Monascus purpureus*	Submerged fermentation	22.25 UA_{500}	Silbir and Goksungur (2019)
Natural Red Pigment	Corn cobs	*Monascus purpureus* KACC 42430	Solid state fermentation	25.42 OD Units/grams	Velmurugan *et al.* (2011)
Lycopene	Tomato Wastes	*Aspergillus niger*	Solid state fermentation	307.2 µg/g	Jamal *et al.* (2017)
Citric acid	Apple pomace	*Aspergillus niger van. Tieghem* MTCC 281	Solid state fermentation	4.6 g/100 g of pomace	Kumar *et al.* (2010)
Lactic acid	Sugar beet pulp; Potato stillage and sugarcane molasses	*Lactobacillus paracasei* NRRL B-4564	Immobilized cell fermentation	2.72 g/g	Mladenovic *et al.* (2017)
Ellagitannase	Sugarcane bagasses	*Aspergillus niger* GH1 strain	Solid state fermentation	400 mg/g	Buenrostro-Figueroa *et al.* (2014)
Xylanase	Barley bran	*Aspergillus niger*	Solid state fermentation	42.02 U/g substrate	Tanash *et al.* (2012)
Phytase	Wheat bran; Sesame oil cake	*Mucor racemosus*	Solid state fermentation	44.5 U/ g substrate	Roopesh *et al.* (2006)
Fungal Chitosan	Potato peels	*Rhizopus oryzae*	Solid-state fermentation	10.8 g/kg substrate	Kleekayai and Suntornsuk (2010)
Fungal Chitosan	Soybean meal	*Mucor rouxii*	Solid state fermentation	34.4 g/kg substrate	Mondala *et al.* (2015)
Oyster mushroom	Paddy straw	*Pleurotus platypus*	Solid state fermentation	1190 g/kg	Dinesh Babu and Subhasree (2010)
Antibiotics (Tetracycline)	Pineapple peel	*Streptomyces aureofaciens* NCIM 2417	Solid-state fermentation	17.98 mg/g substrate	Vastrad and Neelagund (2011)

higher xylitol yield (0.216 g-xylitol/g-xylose) compared to that of acid hydrolysate fermentation (0.100 g-xylitol/ g-xylose). The higher yield obtained from enzymatic hydrolysate fermentation was due to the greater consumption of xylose by yeast to produce xylitol and the absence of inhibitors that can interfere with *D. hansenii* activity. Fermentation rate depends on the concentration of glucose monomers released from cellulose. Kresnowati *et al*. (2015) reported that a high concentration of glucose in hydrolysate resulted in the inhibition of the acid hydrolysate fermentation process of xylose into xylitol. The glucose concentration in the enzymatic hydrolysate decreased faster than that in the acid hydrolysate during fermentation due to the higher utilization of glucose in enzyme hydrolysates as glucose was the dominant food source for *D. hansenii*. In acid hydrolysis, toxic by-products such as furfural compounds formed could act as fermentation inhibitors and thus causing a reduction in xylitol yield. At the end stage of acid hydrolysate fermentation, the microbes utilized xylitol as a food source due to the decreasing amounts of xylose and glucose and consequently decreased xylitol yield. This study indicated that different glucose concentrations and the presence of inhibitors during enzymatic or acid hydrolysate fermentation highly affected the efficacy of xylitol production yield from corn cobs. It was concluded that enzymatic hydrolysate fermentation gave a higher production yield of xylitol.

3.3 Fungal chitosan

Chitosan has been proven one of the best edible and biologically safe preservative coatings for different types of foods because of its film-forming properties, antimicrobial actions, lack of toxicity, biodegradability, and biochemical properties (Sheikh *et al*., 2013). Kleekayai and Suntornsuk (2010) studied the production of fungal chitosan from potato chip processing wastes, namely potato peels by using *Rhizopus oryzae*. Commercial chitosan is usually generated from crustacean shells and has inconsistent physio-chemical properties with poor purity, therefore is undesirable for food application (Badawy and Rabea, 2011). Thus, the production of fungal chitosan from PFW was investigated to obtain more desirable and consistent physio-chemical properties and homogeneous chitosan. A chitosan yield of 10.8 g/kg substrate was obtained from *R. oryzae* fermentation using potato peels as substrate. Another study by Mondala *et al*. (2015) showed that a higher yield of chitosan (34.4 g/kg substrate) can be obtained from *Mucor rouxii* using soybean meals as a solid substrate. Soybean meals contained 50% by weight proteins whereas potato peels contained only 13.7%. Higher protein contents in substrate represent a higher nitrogen source which provides sufficient nutrients to the medium and results in a higher yield of biosynthesis of fungal chitosan.

This fermentation process was conducted under optimized conditions of 50% (w/w) initial substrate moisture content which was favourable to *M. rouxii* strain for fungal growth, pH 5-6 and cultivated for 6 days at 25˚C. Between 6 days to 12 days of the incubation period, the first stationary growth phase was observed. Nwe *et al*. (2010) explained that at the stationary phase, the cell walls of fungal may begin to lose their flexibility and capability for chitosan formation as a result of the aggregation process by chitin crystallization and bond formation and attachment with the other fungal cell wall constituents and thus leads to decreased production.

The best extraction method for maximizing the chitosan yield in this study was autoclaving with 1 M NaOH at 121˚C for 20 mins and volume-to-solids ratio (30:1, mL/g dry mass), then followed by 2% (v/v) acetic acid at 121˚C for 20 mins and volume-to-solids ratio (40:1, mL/g dry mass), representing an alternative extraction condition for fungal chitosan which requires short extraction time.

3.4 Organic acid (lactic acid)

In the study of Mladenovic *et al*. (2017), researchers investigated the potential of using potato stillage and sugar beet molasses as the medium in the fermentation process for the production of lactic acid (LA) and other biomass by cell immobilization absorption of *Lactobacillus paracasei* onto sugar beet pulp (SBP). The highest LA yield (2.72 g/g) was obtained after 62 hrs at 41°C using fermentation of wastes by immobilized *L. paracasei* on SBP as a natural and cheap solid carrier and as a renewable nutrient source without the addition of minerals and nitrogen to the medium. SBP consists of a heterogeneous surface with positively and negatively charged binding sites and *L. paracasei* strains consist of cell surfaces negatively charged in the pH range of 3.8-8.0 (Vučurović and Razmovski 2012). The surface properties of *L. paracasei* strains are hydrophilic and thus lead to a strong *L. paracasei* cells adhesion to the SBP surface. Furthermore, cellular secretion of exopolysaccharides from SBP results in strong cell absorption and consistently great amounts of viable cells attached to the surface of supporting materials. In immobilized cell fermentation, bacterial biomass can be effectively re-used in three batch cycles and resulting in cell regeneration and *L. paracasei* capable of forming a biofilm on the SBP surface for production of higher LA yield as compared to the free cell fermentation.

The average LA productivity in immobilized cell

fermentation (1.03 g/L h) is higher than that of free cell fermentation (0.67 g/L h) due to its high cell density and rapid sugar consumption. The faster fermentation with immobilized cells could be attributed to the reduction of the non-productive growth phase and greater resistance of cells to inhibitory substrates or products (Zhu, 2007). Therefore, utilization of SBP as a solid carrier in immobilized cell fermentation demonstrated an improved conversion efficiency of LA yield as compared to free cell fermentation, whereby the potato stillage and sugar beet molasses can provide sufficient nutrients to the medium which is cost-effective and environmentally safe.

3.5 Enzyme (Phytase)

Roopesh *et al*. (2006) studied the production of phytase enzyme using a mixture of wheat bran and sesame oil cakes (at a ratio of 1:1) as substrates and *Mucor racemosus* in solid-state fermentation (SSF). Phytase production of 32.2 U/gds was obtained under optimum conditions (96 hrs of incubation, inoculum concentration of 1.0 mL of the *M. racemosus* spore suspension, and initial moisture content of substrate at 60%). The addition of 2.0% starch (w/w) to the SSF medium further increased phytase yields to 44.5 U/gds. Starch serves as a carbon source that provides energy for microbe growth. Starch showed the highest effectiveness in improving enzyme synthesis by the fungal culture as compared to glucose, lactose, sucrose, and mannitol. However, further increases in starch concentration inhibited enzyme production. This study demonstrated an economical optimization process for maximizing phytase production.

3.6 Natural pigments

According to Velmurugan *et al*. (2011), *Monascus* pigment (a natural red pigment) was produced by *Monascus purpureus* KACC 42430 in solid-state fermentation using corn cob substrate. The pigment yield using corn cobs substrate (25.42 OD Units/gdfs) was significantly higher than those from other PFW substrates such as wheat bran (3.525 OD Units/gdfs), brewer's spent grain (4.356 OD Units/gdfs), and jackfruit seed (12.113 OD Units/gdfs). This is because corn cobs contain 32 to 35% cellulose and 40% hemicelluloses, and these two complex polysaccharides can be easily broken down by extracellular hydrolytic enzymes of *M. purpureus* into monomers, thus increase the sugars bioavailability which directly improves the growth rate of *M. purpureus* and enhance pigment yield. The maximum red pigment yield (24.18 OD Units/gdfs) was achieved at the optimum conditions with an initial moisture content of 60% (w/w), incubation at 30 °C for 7 days, at pH 5, and inoculum size of 4 mL of spores/g of dry corn cob powder. The mesophilic nature of *M. purpureus* enables maximal growth and pigment production at 30°C and high temperature leads to decreased production. The inoculum size greatly influences the product yield in SSF. Too small inoculum resulted in deficient biomass and little amounts of product, while too large inoculum resulted in too much biomass and used up the nutrients vital for pigment production (Babitha *et al.*, 2007). It was reported that 60% substrate moisture content contributed to effective sugar utilization with maximum glucoamylase activity in the corn cobs substrate. At higher moisture content, agglomeration of substrate occurred and thus reducing the oxygen availability for *M. purpureus*, while too low moisture content caused a decrease in nutrient salt dissolution and reduced efficiency of oxygen transfer and heat exchange, resulting in low nutrient availability for microbe growth and pigment formation (Babitha *et al.*, 2007). This study suggested the feasibility of using corn cob substrate in cooperation with *M. purpureus* for industrial production of *Monascus* pigment due to its low cost and being environmentally friendly.

4. Conclusion

Substantial amounts of valuable products such as lignocellulosic materials and bioactive compounds can be derived from various plant-derived food wastes. The high-value products include natural antioxidants, pigments, alternative sweeteners, enzymes, and other bioingredients which have potential applications in the production of functional foods and pharmaceutical products. Type of substrates, fermentation methods, and optimization of bioprocess conditions are important factors for high production yields of these high-value products. Plant food wastes have been associated with global concerns such as climate change, biodiversity damage, and socio-economic issues. The exploitation of plant food wastes for valuable products through bioprocesses has significant implications for environmental protection, public health, and economic gain.

Conflict of interest

The authors declare no conflict of interest.

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