Bioconversion of Fruits and Vegetables Wastes into Value-Added Products

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Abstract

The increase in human population with the increase in nutritional awareness for fruits and vegetables consumption is forcing toward higher production and supply of fruits and vegetables. However, some sorts of food processing steps are involved before human consumption which is essential for preserving the properties of those fruits and vegetables. During these processes and till reaching the consumers, many fruits and vegetables wastes are produced. Although the emphasis was given to produce less waste and reuse the products as much as possible, utilization of those wastes in bioprocessing and production of different value-added products were less emphasized. Thus, in this chapter, we describe the major value-added bioproducts produced from fruits and vegetables wastes such as bioactive compounds, phenolic compounds, enzymes, pigments, flavoring compounds and aroma, dietary fibers, organic acids, bioenergy, bioplastics, exopolysaccharides, single-cell protein, etc.

Keywords

Value-added products • Bioconversion • Bioactive compounds • Single-cell protein • Bioenergy • Bioplastics • Exopolysaccharides

1 Importance of Fruits, Vegetables, and Their Waste

Human population of the world is continuously increasing with a growth rate of 1.05% per year reaching a population of over 7.7 billion and, by 2030, it is predicted to reach 8.5 billion (United Nations 2019). With the limited natural resources, it is difficult to supply food to the growing population. At the same time, due to the rising human population, there is a high demand for food production. Fruits and vegetables (FV) consumption is considerably increased with the increase in awareness of FV and their health benefits to humans. FV are fundamental for human nourishment as they contain significant amounts of minerals, vitamins, and fibers. The consumption of natural and high-quality FV is also increased for healthier lifestyles (FAO 2016). Moreover, the consumption of FV imparts in reducing the threat of stroke, some cancer, and coronary heart disease. Health welfare of these kinds is chiefly credited to natural micronutrients like vitamin C, carotenoids, tocopherols, polyphenolics, etc. The organic micronutrients are available in colored (yellow and green) vegetables and citrus fruits. Although a large population is conscious of their health problems connected with nutrition, they lack plentiful intake of FV and there is a need to find out the alternate option to get these micronutrients (Schieber et al. 2001). At the same time, most of the population do not consume raw FV in many cases and these FV need to undergo some kind of processing. Thus, during the processing of FV, large masses of wastes are generated. Regrettably, FV depletion rates are high and depend upon the types of fruits. Fruits from temperate zones produce less amount of waste compared to fruits from tropical and subtropical zones (Schieber et al. 2001; Kodagoda and Marapana 2017).

It is anticipated that 1/3rd of all food harvested is lost or dumped as waste in the world (FAO 2019) throughout the food supply chain. Global scenarios of some FV wastes production are shown in Table 1. Thus, there is a need to decrease food loss or waste along with the production as well

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Inamuddin and A. Khan (eds.), *Sustainable Bioconversion of Waste to Value Added Products*, Advances in Science, Technology & Innovation, https://doi.org/10.1007/978-3-030-61837-7_9

as in different stages of food supply chain. In addition, a huge amount of food waste is also generated in different food processing industries (FAO 2019; Ravindran and Jaiswal 2016). These food wastes are classified into two major groups as the waste obtained from plants and the waste obtained from animals based on biochemical characteristics of food waste and origin. The wastes obtained from animals are mainly produced from the dairy, meat, fisheries, and seafood processing industries. Similarly, plant-derived wastes include different types of residues obtained from different crops including FV (Ravindran and Jaiswal 2016). These FV are produced seasonally and overproduction during the season must be stored properly for future use. However, the perishable nature of FV, inappropriate storage conditions mainly in tropical regions lead to increased production of waste. In addition, the remains of FV like stem, stalks, leaves, roots, and tubers impart in waste. FV processing waste includes pomace, peels, and seeds accounting for 25–30% waste. Thus, it is revealed that FV losses or wastes are mostly due to post-harvest grading quality standards of FV set by retailers. This type of loss and deterioration of crops mainly occur in hot and moist climates, the seasonality that results in insufficient access (FAO 2019).

According to FAO (2011) a combined data from Canada, New Zealand, the USA, and Australia nearly half the amount of the FV produced in the world annually end up as wastes (FAO 2011) in the garbage. Other factors like improper drying, storage, and transportation play important roles in the production of FV waste. FV processing industries generate a larger portion (30–50%) of fruits and vegetable waste (FVW) as by-products during different stages of processing, distribution, and consumption (Di Donato et al. 2011). Moreover, the fruit wastes are also generated during the production of pickle, puree, sauces, fresh-cut fruit, canned fruit, juices, dehydrated fruit, jams, etc. (Di Donato et al. 2011; Coman et al. 2020).

2 Potentials of FVWs in Production of Value-Added Products

FV are organic matter and contain macronutrients like proteins, lipids and carbohydrates, bioactive compounds, and phytochemicals. The high costs of drying, storing, and transportation of the organic wastes produced during different processes make them used as feed or composted to produce

Table 1 Global scenario of fruits and vegetables waste production adopted from Uçkun-Kiran et al. (2014), Caldeira et al. (2019), CEC (2017), Oelofse (2014), Tran and Mitchell (1995)

Wastes	Asia	South Africa	North America	Europe	Australia	References
Potatoes/tubers	12,912 KT	955000 T	244 MT	9.4 Mt	23.6 KT	Uçkun-Kiran et al. (2014), Caldeira et al. (2019), CEC (2017), Oelofse (2014)
Cereals	52,374 KT	2605000 T	317 MT	15.6 Mt	1380 KT	Uçkun-Kiran et al. (2014), Caldeira et al. (2019), CEC (2017), Oelofse (2014)
Oil crops	13,590 KT	NR	43 MT	12.7 Mt	3.9 KT	Uçkun-Kiran et al. (2014), Caldeira et al. (2019), CEC (2017)
Vegetables	59,949 KT	2020950 T	NR	31.3 Mt	54.1 KT	Uçkun-Kiran et al. (2014), Caldeira et al. (2019), Oelofse (2014)
Apples	4116 KT	NR	NR	NR	5.9 KT	Uçkun-Kiran et al. (2014)
Bananas	8544 KT	NR	NR	NR	5.4 KT	Uçkun-Kiran et al. (2014)
Pineapple/peel	579 KT	NR	NR	NR	400 KT	Uçkun-Kiran et al. (2014), Tran and Mitchell (1995)
Fruits	28,328 KT	2470050 T	NR	28.1 Mt	30.9 KT	(Uçkun-Kiran et al. (2014), Caldeira et al. (2019), Oelofse (2014)
Fruits and vegetables	88,277 KT	4491000 T	492 MT	59.4 Mt	85 KT	Uçkun-Kiran et al. (2014), Caldeira et al. (2019), Oelofse (2014)

Note T: ton, KT: kiloton, Mt: metric ton, MT: million ton, NR: not reported fertilizer or discarded in rivers or banks causing conservational hazard (Kodagoda and Marapana 2017; Coman et al. 2020; Wadhwa et al. 2013). Thus, lately many researches have been going and more attentiveness has been given on the recovery of value-added products like the bioactive compounds possessing health benefits for humans from industrial by-products (Coman et al. 2020). Additionally, FVWs contain high moisture, a good pool of lipids, complex carbohydrates, nutraceuticals, proteins, and fats. Therefore, these wastes are recycled to be used as feed resources or can be commercially utilized as the raw materials for the production of essential metabolites. FVWs are exploited by certain microbes and transformed into value-added products adding an economical value of FVWs. This approach of utilizing resources from wastes creates possibilities in the development and contributes in the justifiable improvement of livestock industries (Ravindran and Jaiswal 2016; Wadhwa et al. 2013; Panda et al. 2016). The effective and efficient utilization of FVWs will increase farmers' profits, reduce the cost of animal feeding, generate different profitable products, aid in waste management, and reduce pollution. Different FVWs such as cauliflower leaves, corn husk, cabbage leaves, pea pods, leafy waste of mustard, tomato pomace, citrus waste, carrot waste, mango peels, bottle gourd pulp, banana peel, etc., can be directly fed to animals or following drying or ensiling with crop straws. These dried or ensilaged animal feeds do not affect nutrient deployment, health, lusciousness, and functioning of livestock. The FVWs can be utilized in the production of edible oil, essential oils, pigments, polyphenols, enzymes, bio-methane, bioethanol, bioplastic, anti-carcinogenic compounds, single-cell proteins, and more (Wadhwa et al. 2013). The overall simple diagrammatic representation of converting the FVWs into products adding value is presented in the Fig. 1.

To fulfill the increasing demand of food for the growing population, valorization of food supply chain waste should be studied so that it helps to design different opportunities for the production of bioactive compounds, biofuels, bioplastics, enzymes, and more. The waste management problem is exaggerated due to ineffective waste management leading to slow actions on appropriate conduct, treatment, and disposal of waste (Ravindran and Jaiswal 2016). However, the common and easy waste management strategy is to prioritize lessening waste production and minimum importance on discarding.

3 Conversion Process

The FVWs and other by-products produced from food industries can be used in the production of different value-added products mainly by three processes; thermal conversion, chemical conversion, and biological conversion (Singh et al. 2019). The appropriate conversion method depends on the composition of wastes and by-products and the aim of the recovery process.

3.1 Thermal Conversion

This process includes incineration, hydrothermal carbonization, pyrolysis, and gasification. Incineration implicates the burning and alteration of waste constituents into heat and energy and also decreases the volume of solid waste up to 80–85%. This technique of combusting solid waste is antiquated, and food waste seems to be unsuitable for incineration due to moisture content in FVWs. However, this technique may be beneficial when used after drying of FVWs with respect to energy loss. The heat generated from the combustion process is generally consumed by steam turbines for producing energy or for exchanging heat (Pham et al. 2015). Thus, the thermal treatment of waste is applied with the precise aim of generating power (Singh et al. 2019).

Hydrothermal carbonization (HTC) is an aqueous carbonization process performed at a relatively lower temperature (180–350 °C) and autogenous pressure. This process is suitable for wet or high moisture containing wastes which alters the food trashes into an energy-rich valuable resource (Pham et al. 2015). This process has various advantages such as it is faster than biological processes, removes many organic impurities and pathogens, and reduces waste volume. HTC process results in the production of highly carbonized and energy-containing material known as hydrochar which is equivalent to lignite coal. The hydrochars can be used in removing dyes from polluted water (Singh et al. 2019; Pham et al. 2015).

Gasification and pyrolysis are also thermal processes that effectively work against food wastes containing carbon. Gasification is the process in which waste is converted into a mixture of combustible gas by partial oxidation at temperature 800–900 °C. Similarly, pyrolysis is the process which converts waste into bio-oil, solid biochar, and syngas. The produced combustible gas can be burned directly or can be used as a feedstock in methanol production (Pham et al. 2015).

3.2 Chemical Conversion

This process is commonly applied in food processing industries and includes hydrolysis, oxidation for producing value-added products from food waste (Singh et al. 2019). The chemicals (acid or alkali) help to disrupt the cell and extract the compounds. New and alternative solvents with enhanced physical properties are being used as extraction solvents such as propane, butane, dimethyl ether for extraction of natural products like oils, antioxidants, aromas.

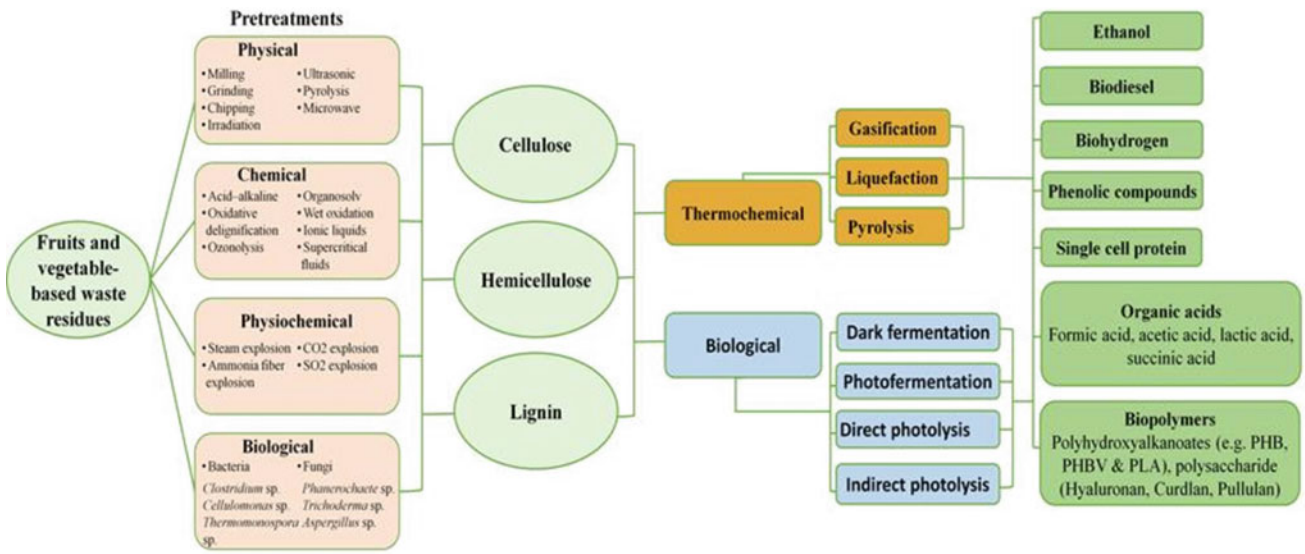

Fig. 1 Schematic demonstration of the conversion of fruits and vegetables wastes into value-added products

Valuable by-products and materials can be extracted by green extraction techniques like high-voltage electrical discharge and pulsed electric field technology. In both technologies, electroporation occurs, and cell permeability is increased so that extraction of intracellular compounds is enhanced (Chemat et al. 2020; Sarkis et al. 2015). Extraction of antioxidants from potato peels with ethanol was executed by Amado et al. The antioxidant extraction was related to the process conditions like temperature, time, and ethanol concentration (Amado et al. 2014).

3.3 Biological Conversion

This process is becoming more common and gaining interest throughout the world. Energy, bioactive compounds, and value making products can be recovered from organic wastes by the biological conversion involving anaerobic digestion and fermentation. Anaerobic digestion is the process of microbial catabolism in which organic wastes decompose and produce biogas mainly methane, and traces of nitrogen, CO_2, hydrogen sulfide in absence of oxygen. Fermentation process includes either solid-state fermentation (less water/moisture content) or submerged state fermentation (very less or absence of water/moisture content). Different factors such as pretreatment, kinds/quality of substrates, and microbes used play an important role. Biological conversion is eco-friendly, environmentally safe, protective to human health, and can minimize carbon dioxide, methane like gas emission (Singh et al. 2019; Awasthi et al. 2019). Vegetable wastes such as tomato, fennel, carrot, and more can be used as a cheap carbon substrate for microbial culture without chemical pre-treatment. These FVWs can be used as environment-friendly and low-cost substrates in culture media for the manufacture of biomolecules such as enzymes and biopolymers using some specific microorganisms (Di Donato et al. 2011).

4 Bioconversion of FVWs into Different Value-Added Products

As the fossil-based resources are diminishing, alternate feedstock for producing chemicals and fuels needs to be secured or explored out. Different biomass in a form of organic wastes produced are being an interesting subject for their exploitation as renewable resources. The organic wastes have been considered as a valuable feedstock in generating varieties of intermediates and products. For example, some furans and organic acids are usually used as chemical precursors to manufacture various products including polymers, biosurfactants, biolubricants, or nanoparticles (Esteban and Ladero 2018). Some of the value-added products produced from FVWs are listed in Table 2. These products have various uses in industries, due to their similar functioning as recognized products. The waste management systems begin with waste minimization. Therefore, to achieve waste minimization in the industry, it is beneficial to use further effective approaches such as in-house recycling of waste, reuse of waste products, and upgrading of waste property. FVWs are greatly rich in starch, inulin, hemicellulose, pectin, and cellulose like polysaccharides and thus can be used as resources for producing a wide array of products such as antibiotics, biofuels, vitamins, enzymes, pigments, livestock feed, and more (Sadh et al. 2018).

4.1 Bioactive Compounds

Bioactive compounds comprise a wide variety of natural compounds which can be found mainly in different colored FV and offer tremendous storage of food additives, nutraceuticals, and functional foods. Natural sources of bioactive compounds are plants, fruits, tea, olive, algae, bacteria, and fungi. Polyphenols like compounds can be discovered in the environment at extreme intensity relative to other compounds. So, to extract sufficient amounts of bioactive compounds improved and advanced technologies need to be applied. The common bioactive compound extraction methods are pressurized liquid extraction, solid–liquid, or liquid–liquid extraction, ultrasound-assisted and microwave extractions, enzyme and instant controlled pressure drop-assisted extractions, and supercritical and subcritical extractions (Gil-Chávez et al. 2013). The FVWs mainly contain sterols, tocopherols, carotenes, terpenes, polyphenols, dietary fibers like bioactive compounds which are value-adding compounds (Kumar et al. 2017). With an increase in food processing industries by-products and losses of FV, there is an increase in the amount of FVWs. Thus, the FVWs can be an alternative source to produce bioactive compounds which will help to make farmers financially stronger and cut the problem of managing waste.

4.1.1 Phenolic Compounds

Phenolic compounds are an assembly of diverse molecules categorized as secondary metabolites widely found in plants. The most commonly studied bioactive phenolic compounds from FVWs have health beneficial properties like cardioprotective, anticarcinogenic, antioxidant, and anti-inflammatory (Haminiuk et al. 2012; Balasundram et al. 2006). The phenolic compounds generally possess an aromatic ring having hydroxy substituents. Of various compounds, tannins, flavonoids, and phenolic acids have dietary functions. These substances are produced by plants throughout their ordinary growth and in response to different situations like biotic stress and UV radiation (Rispail et al. 2005). The type and number of phenolic compounds found in fruits depend on many factors; types and maturity of fruits, geographic location, soil composition, climate, storing conditions, etc. (Robards et al. 1999). Varieties of FVWs produced as a residue of asparagus, grape, olive, citrus, apple, onion, pomegranate, potato, mango, carrot, banana, etc., can be worthy sources of phenolic compounds (Kumar et al. 2017). The phenolic compounds act as antioxidants and asa substrate for oxidation reaction. The extraction and recovery of phenolic compounds are complicated because these compounds are highly reactive and are unevenly distributed in various forms. The soluble form of phenolic compounds is mainly located in vacuoles (Rispail et al. 2005). Extraction, as well as recovery of phenolic compounds, are done following submerged or solid-state fermentation methods. However, the most commonly used is solid-state fermentation due to high efficiency, high yield, shorter time, and less costly (Martins et al. 2011).

Phenolic acids include hydroxybenzoic acid (syringic, vanillic, gallic acid) plus caffeic, sinapic, ferulic acid like hydroxycinnamic acids. Flavonoids are the largest group of plant phenolics, having few molecular compounds. Tannins are the third important group of phenolics and have relatively high molecular weight and include hydrolyzable and condensed tannins (Balasundram et al. 2006).

Flavonols and flavones are commonly found in plants. One or more hydroxyl groups are bound to a sugar unit (most commonly glucose) with rhamnose and the disaccharide (Balasundram et al. 2006). Anthocyanins are another most common and widely found flavonoids which are accountable for blue, red, and violet colors of some FV, although red color of orange and tomato is due to carotenoid. In ripe berries, five classes of phenolic compounds such as phenolic acid, flavonol, flavones, flavanonols, and anthocyanins are well present. In different types of grapes, different phenolic compounds are found. For example, red grapes have anthocyanins, whereas white grapes have flavonols. The most common citrus fruits have only rutinosides that are non-bitter but pummelo and sour oranges have only flavanone neohesperidosides giving bitter taste. However, some citrus fruits like grapefruit include both neohesperidosides and flavanone rutinosides. Phenolic compounds like malvidin glycosides formed during wine maturation are unaffected by sulfur dioxide bleaching. Cinnamic acid is a foremost portion of phenolic compounds found in citrus fruits (Robards et al. 1999). The concentration of phenolics is different within plant tissues (Balasundram et al. 2006). Some simple food processing like peeling of FV can abolish a substantial share of polyphenols. In some fruits such as grapes, the high concentration of these substances is often present in the skin than in the pulp. For example, tannin is complex polyphenols commonly found in the skin and seed of grape berry. The concentration of tannins is not exactly the same in wine produced from grapes and in the fresh harvest fruit. Tannin is lower in wine produced from grapes compared to fresh grapes due to loss of these compounds during pressing and fermentation. Conversely, maximum of the main solutes existing in the grape berry at harvest time are present in wine composition. Limited digestion process, physical and thermal processing, and mastication help in the absorption of the phenolic compounds in the intestine. Sometimes, nutrients released during digestion may interact with other food components and form complex and colloidal structures which may affect in absorption (Parada and Aguilera 2007). Phenolic compounds are used as dietary

Table 2 Potential value-added products from fruits and vegetables wastes

Different wastes	Value-added products	References
Pineapple waste	Biogas, ethanol, hydrogen, lactic acid, citric acid, ascorbic acid, ferulic acid, furaneol, vanillin, fiber	Choonut et al. (2014), Dorta and Sogi (2017), Leong and Shui (2002)
Grape waste	Phenolic compounds, essential oil (Oleic and linoleic acid), tartaric acid, lactic acid, hydrolytic enzymes, Polyhydroxyalkanoates, anthocyanin	Teles et al. (2019), Follonier et al. (2014), Shinagawa et al. (2015)
Potato waste	Chlorogenic, ferulic acid, pullulan, lipid, cellulolytic enzymes, livestock feed	Wadhwa et al. (2013), Amado et al. (2014), dos Santos et al. (2012), Muniraj et al. (2015), Esparza et al. (2020)
Banana waste	Single-cell protein, polymers (lignin, hemicellulose, pectin), sterols, anthocyanin, carotenoids, phenolic compound, ascorbic acid, bioethanol, amylase	Unakal et al. (2012), Ingale et al. (2014), Malav et al. (2017), Leong and Shui (2002), Someya et al. (2002)
Pomegranate waste	Single-cell protein, phenolic compounds, ascorbic acid, dietary fiber, ferulic acid	Tilay et al. (2008), Malav et al. (2017), Li et al. (2006)
Orange waste	Single-cell protein, pectin, pectinase, ascorbic acid, ferulic acid, curdlan	Ahmed et al. (2016), Tilay et al. (2008), Esparza et al. (2020), Mondal et al. (2012), Malav et al. (2017), Leong and Shui (2002)
Watermelon waste	Single-cell protein, ascorbic acid	Malav et al. (2017), Leong and Shui (2002)
Sweet beet waste	Livestock feed, single-cell protein	Wadhwa et al. (2013), Malav et al. (2017)
Cucumber waste	Single-cell protein, flavonoids, flavanols	Mondal et al. (2012), Agarwal et al. (2012)
Coconut waste	Xanthan, curdlan, ascorbic acid, phenolic compounds	Esparza et al. (2020), Leong and Shui (2002), Dey et al. (2003)
Date palm waste	Xanthan, curdlan	Esparza et al. (2020)
Asparagus waste	Curdlan	Esparza et al. (2020)
Canola oil waste	Biodiesel	Lee et al. (2012)
Cassava waste	Curdlan, pullulan, animal feed, lipid, biodiesel	Ajila et al. (2012), Muniraj et al. (2015), Esparza et al. (2020), Lu et al. (2011)
Apricot waste	Succinic acid, lactic acid, polyhydroxyalkanoates	Follonier et al. (2014)
Cherries waste	Lactic acid, succinic acid	Follonier et al. (2014)
Sweet potato waste	Lipid, citric acid	Muniraj et al. (2015), Yu et al. (2017)
Corncob waste	Lactic acid, formic acid, citric acid, succinic acid, protease, amylase, protease, lipid, biodiesel	Di Donato et al. (2011) Kandasamy et al. (2016), Kong et al. (2019), Muniraj et al. (2015), Venkata and Venkata (2010)
Apple waste	Ascorbic acid, flavonoids, flavonols, pectin, anthocyanin, enzymes, single-cell protein, aroma compound, ethanol, organic acid, livestock feed	Wadhwa et al. (2013), Vendruscolo et al. (2008), Leong and Shui (2002), Wolfe and Liu (2003), Schieber et al. (2003)
Mango waste	Carotenoid, dietary fiber Ascorbic acid Furaneol Oleic and linoleic acid Livestock feed	Wadhwa et al. (2013) Pickenhagen et al. (1981), Leong and Shui (2002) Ajila et al. (2010), Kittiphoom and Sutasinee (2013)
Citrus waste	Pectin, pectinase, flavonol, phenolic acid, livestock feed	Wadhwa et al. (2013), Robards et al. (1999), Dhillon et al. (2004), Bocco et al. (1998)

(continued)

Table 2 (continued)

Different wastes	Value-added products	References
Tomato waste	Polysaccharides, polyphenols, ascorbic acid, livestock feed	Di Donato et al. (2011), Wadhwa et al. (2013), Leong and Shui (2002)
Avocado waste	Phenolic compound, ascorbic acid, carotenoid, fiber	Chemat et al. (2020), Leong and Shui (2002)
Papaya waste	Ascorbic acid	Leong and Shui (2002)
Bottle gourd waste	Cellulase, animal feed	Wadhwa et al. (2013), Verma and Kumar (2020)
Carrot waste	Biopolymers, polysaccharides, enzymes, polyphenols, livestock feed	Di Donato et al. (2011), Wadhwa et al. (2013)
Amla pulp	Polyphenol, flavonoid	Agarwal et al. (2012)
Lemon waste	Polysaccharides, enzymes, polyphenols, flavonoid	Di Donato et al. (2011), Agarwal et al. (2012)
Food processing waste	Hydrogen, bioethanol, biobutanol	Zhang et al. (2016)
Agro-industrial wastes	Pigments	Panesar et al. (2015)

supplements and food fortification for health benefits and prefer natural sources that are not able to synthesize chemically and need to be extracted from original plant material (Schieber et al. 2001).

4.1.2 Enzymes

Enzymes are biological catalysts, proteinaceous, and catalyze a number of metabolic processes. Enzymes are applied in different industries for the production of a wide variety of products. For instance, pectinases and amylases are used in food industries, cellulases in biofuel industries, and tannases in reducing the tannic acid amount in effluents. However, raw materials used for the production of different enzymes account for about 30% of the operation cost (Ravindran and Jaiswal 2016). Plant-related food wastes mainly contain cellulose, hemicellulose, lignin, starch, xylan, pectin, glucan, etc., depending upon the nature of waste products. Most commonly applied enzymes are amylases, cellulases, hemicellulases, ligninases, pectinases, tannases, proteases, lipases. Microorganisms can be utilized for the production of different enzymes and the rate of enzyme production varies with the organisms growing on dissimilar substrates and different methods of fermentation.

Enzymes Acting on Polysaccharides

i. Amylases: This group of enzymes composed of glucoamylase, β-amylase, and α-amylase which hydrolyze starch, oligosaccharide, and polysaccharides into glucose, fructose, maltose sugars. Amylases are classified in exo-amylase and endo-amylase based on the hydrolysis of starch (Panda et al. 2016). Many FVWs such as banana waste (Unakal et al. 2012), date waste (Said et al. 2014), apple pomace (Nigam and Singh 1994), and potato peel (Mushtaq et al. 2017) have been used in amylase production. Microorganisms like *Candida guilliermondii*, *Aspergillus niger*, *A. tamarii*, *A. oryzae*, *Bacillus licheniformis*, *B. subtilis*, *Thermomyces lanuginosus*, and *Rhizopus oryzae*are exploited for amylase production (Unakal et al. 2012; Said et al. 2014; Nigam and Singh 1994; Mushtaq et al. 2017; Metha and Satyanarayana 2016). Amylases are widely used in baking, brewing, and preparation of digestive aids such as for the production of sugar, paper, moist cakes, fruit juices, chocolate cakes, starch syrup, and more (Metha and Satyanarayana 2016).

ii. Cellulases: This group of enzymes is comprised of exoglucanase (cellobiohydrolase), endo-β-glucanase, and β-glucosidase which hydrolyze cellulose into glucose, cellobiose, and other oligosaccharides. The three main cellulases act synergistically to cleave the glycosidic linkage of cellulose and completely hydrolyze the cellulose present in plant wastes. Exoglucanase cleaves the long chain from endings (reducing or non-reducing), endoglucanase cleaves the long oligosaccharides into short oligosaccharide chain, and β-glucosidase further hydrolyze to glucose (Kuhad and Gupta 2011; Juturu and Wu 2014). Vegetable waste like bottle gourd peel can be the substrate for producing cellulase by *Neurospora crassa* and *Trichoderma reesei* (Verma and Kumar 2020), potato peel by *Aspergillus niger* (dos Santos et al. 2012). Cellulases are applied in animal feed, food, and brewery production, textile processing, detergent production, and pulp paper manufacture. Recently, the increasing demand for biofuels and chemicals recovered from renewable resources has made cellulases to be exploited for producing fermentable sugars in cellulose biorefinery (Kuhad and Gupta 2011).

iii. Hemicellulases: This group of enzymes integrates α-arabinofuranosidases, α-glucuronidases, mannanases, and α-d-galactosidases that attack the β-1,4-glycosidic bonds of hemicellulose in lignocellulosic biomass. Hemicellulases are efficient in breaking esterified side chain groups as well as glycosidic bonds.

Mannanases destroy mannan which is the basic part of the plant cell wall commonly in plant seeds and fruits. The group of enzymes included in mannanases is β-mannanases, β-mannosidases, and β-glucosidases (Malgas et al. 2015; Chauhan et al. 2012). Mannan plays an essential role as seed storage compounds and in an arabidopsis mutation where (gluco)mannan synthase lacks (Malgas et al. 2015; Goubet et al. 2003). *Bacillus* sp., *Aspergillus* sp., *Clostridium* sp., *Streptomyces* sp., *Trichosporonoides oedocephalis*, etc., have the ability to produce mannanases. They use apple pomace, plantain peels, mango peels, potato peels, passion fruit peel, etc., as substrates for mannanase production. Mannanases are applicable in industries like pharmaceutical, pulp and paper, food, oil, feed, textile and detergent industries, and coffee extraction (Chauhan et al. 2012).

iv. Pectinases: This includes a group of enzymes such as pectinesterase, polygalacturonase, pectin lyase, and pectate lyase which hydrolyze pectin. Pectin is a kind of polysaccharide which gives rigidity and structure and is present in the primary cell walls and middle lamella of plants. These classes of enzymes are most commonly used for the production and clarification of fruit juices. Pectinases can be produced from wastes of strawberry pomace, orange peel, cranberry pomace, apple pomace, citrus peel, sugarcane bagasse, etc., when used as a substrate by *Aspergillus niger* strains (Dhillon et al. 2004; Ahmed et al. 2016). Some pectinase-producing microbes are *Aureobasidium* sp., *Candida* sp., *Cryptococcus* sp., *Klebsiella* sp., *Kluyveromyces* sp., *Penicillium* sp., *Bacillus* sp., *Pseudomonas* sp., *Rhizopus* sp., *Rhizomucor* (Amin et al. 2019). Pectinases are being exploited in wine industries, paper and pulp industries, wastewater treatment, bioethanol production, extraction of DNA from a plant, and protoplast isolation from a plant. In addition, pectinases are expended in the production of animal feed, saccharification and liquefaction of biomass, oil extraction, bio-scouring of cotton fiber, retting and degumming of plant fiber, and tea and coffee fermentation (Kubra et al. 2018; Kashyap et al. 2001). Moreover, pectinases are also used in feed to remove all the antinutritional properties of pectin, augment the viscosity of plant products, and progress digestion in animals (Ajila et al. 2012).

v. Xylanase: Xylanases are a complex and very important group of carbohydrolases. This enzyme group consists of α-glucuronidase, ferulic acid esterase, endo-xylanases, β-xylosidases, p-coumaric acid esterase, and acetyl xylan esterase which breakdown xylan (an important plant polysaccharide) (Beg et al. 2001). Orange discards, apple pomace, sorghum straw, lemon pomace, pear peel, lemon peel, banana peel, soya bean hull, melon peel, and hazelnut casing are used to produce xylanase by *Trichoderma harzianum* (Seyis and Aksoz 2005; Couto 2008), and grape pomace used as substrate by *Aspergillus niger* to produce xylanase (Teles et al. 2019). Xylanases are employed in animal feed industries, food like bread and biscuit industries, wine and beer industries, textile and paper industries, biofuel production, deinking of waste paper. Some of xylanases-producing microorganisms are *Arthrobacter, Micrococcus, Bacillus, Paenibacillus*, *Staphylococcus*, *Streptomyces, Nonomura, Flavobacterium, Cellulomonas, Chaetomium thermophilum, Humicolainsolens, Thermoascus auranticus*, *Actinomadura*, *Microbacterium, Rhodothermus*, and *Pseudoxanthomonas* (Alokika 2019; Chakdar et al. 2016). Xylanase together with pectinase and cellulase are commonly used in extracting and clarifying fruit juices and liquefaction of fruits and vegetables (Alokika 2019). Similarly, xylanase with phytase and cellulase in animal feed enhance digestion and absorption of nutrients and xylanase with cellulase and laccase are applied to generate ethanol (Chakdar et al. 2016).

Enzymes Acting on Proteins

i. Proteases: These enzymes are the proteolytic enzymes that break down peptide bonds between amino acids in polypeptide chains. Proteases are one of the frequently significant industrial enzymes used in detergent, food, pharmaceutical, leather, textile, and silk industries. Based on the catalytic residues in the functional site, proteases are sub-categorized into metalloproteases, serine proteases, cysteine proteases, glutamic acid proteases, aspartic proteases, and threonine proteases (Singh et al. 2016). *Bacillus* sp. like *B. licheniformis, B. lentus, B. amyloliquefaciens,* are the most exploited in the industrial sector for protease production (Razzaq et al. 2019). *Aspergillus* sp., *Serratia liquefaciens, Flavobacterium balustinum, Penicillium* sp., *Rhizomucor* sp., *Rhizopus* sp., *Thermoascus aurantiacus, Trichoderma reesei,* etc., are also the proteases producers (Singh et al. 2016). Proteases formed *by Conidiobolus coronatus, Streptomyces avermectnus, and Bacillus subtilis* are used in photographic industries to retrieve silver (Razzaq et al. 2019). Plant also produces proteases which are broadly consumed in food industries and medicine. The varieties of plant proteases (bromelain, papain, ficin) are used in milk clotting, brewing, cancer treatment, meat softening, viral and digestion disorders (González-Rábade et al. 2011). FVWs like jackfruit seed powder, palm kernel cake, olive oil, corncobs, green gram husk, sesame oil cake, black gram husk, chickpea husk (Sandhya et al. 2005; Kandasamy et al. 2016; Prakasham et al. 2006), potato peel, pomegranate peel, karat peel, and mango peel (Panda et al. 2016) can be used as a substrate for proteases production.

ii. Transglutaminases: This collection of enzymes are transferase enzymes catalyzes the formation of isopeptide bonds between proteins. Transglutaminases are also known as protein–glutamine γ-glutamyl transferases. *Actinomadura* sp., *Bacillus circulans*, *B. subtilis*, *Corynebacterium* sp., *Enterobacter* sp., *Streptomyces* sp., *Streptoverticillium* sp. are some of the transglutaminase producers (Kieliszek and Misiewicz 2014). Transglutaminases are used to produce various dairy products, in processing of meat, producing bakery products, and edible films. Transglutaminase has noteworthy impending to enhance viscosity, firmness, water-binding capacity, and elasticity of food products (Kieliszek and Misiewicz 2014).

Other Enzymes

i. Tannase is also known as tannin acyl hydrolase which hydrolyzes tannin into glucose and gallic acid. Gallic acid produces propyl gallate and trimethoprim (Lekha and Lonsane 1997). Various agricultural residues; *Syzygiumcumini*, *Phyllanthus emblica*, *Acacia nilotica,* and *Eucalyptus glogus* (Kumar et al. 2016), *Acacia nilotica, Phyllanthus emblica*, *Syzygiumcumini*, *Zyzyphus mauritiana*, *Eugenia cuspidate* leaves (Selwal et al. 2011) generate tannase by specific organisms. Tannase-producing microbes are *Aspergillus, Penicillium* (Batra and Saxena 2005), *Rhizopus oryzae* (Hadi et al. 1994), *Bacillus licheniformis* (Das Mohapatra et al. 2006), *Klebsiella pneumoniae* (Kumar et al. 2016).

Tannin is present in many edible FV, but they are well-thoughtout as disadvantageous nutritionally because they form complexes with digestive enzymes, starch, protein, and decrease the nutritive significance of food. Tannases are considerably used as a clarifying agent in beer and wine, in producing instant tea, in reducing fruit juices astringency, decreasing anti-nutritional effects of tannins in animal feed, removing tannin from the effluent of leather industry, chemical, and pharmaceutical industries (Lekha and Lonsane 1997; Selwal et al. 2011).

ii. Laccases are the enzymes that have potential to oxidize both non-phenolic and phenolic lignin associated and very recalcitrant compounds. These are used in the reclamation of effluents produced from petrochemical and textile, pulp and paper industries, delignification of lignocellulose, in water purification systems, as a bioremediation agent in soil, tool for medical diagnostics, catalysts for producing constituents in cosmetics, and anti-cancer drugs (Couto and Herrera 2006; Wang 2013). Some of the microbes including *Pleurotusostreatus, Aspergillus, Coriolopsis, Pleurotuscinna barinus, Streptomyces cyaneus, Trametesmodesta, T. versicolor*, *T. trogii, Cladosporium* sp. are laccases producers (Couto and Herrera 2006; Yang et al. 2015). Different FVWs such as apple residues, sugarcane bagasse, apricot seed shell, corncob, etc., are used for laccase production (Yang et al. 2015; Birhanli and Ye silada 2013).

iii. Inulinases act upon inulin which is a polyfructose chain linked by β-2,1-linkage and ends with a glucose unit producing fructose. Inulinases are applied in manufacturing butanediol, lactic acid, citric acid, and bioethanol. Some known inulinases producer are *Actinomyces viscosus, Penicillium* sp., *Saccharomyces* sp., *Chrysosporium pannorum, Streptococcus salivarius, Aspergillus niger, Fusarium oxysporum*, and *Kluyveromyces fragilis* (Chi et al. 2009). Organic low-cost substrates applied for inulinase production are banana peel, orange peel and bagasse, sugarcane bagasse, etc. (Onilude et al. 2012).

4.2 Pigments

The food leftover has high values for biological oxygen demand causing problems in its collection, treatment, disposal, and losing the precious raw materials. The cheaply available FV residues can be used effectively for microbial pigment production that are helpful for making processes economic and eco-friendly. Microbial biotechnology has developed new possibilities for immense utilization of waste in the production of augmented products via fermentation process rather than conventional applications like making compost or feeding cattle as fodder (Panesar et al. 2015). The various synthetic colorants have carcinogenic and teratogenic properties. Thus, food containing synthetic colorants is being avoided and the stipulation for naturally and safely appearing eatable color has increased. Food industries are replacing them with natural pigments like betalains, carotenoids, anthocyanins, and carminic acid. Beetroot (both yellow and red beetroot), colored leafy or grainy amaranth, cactus fruits, and swiss chard contain water-soluble nitrogenous pigments known as betalains. Betalain is composed of yellow betaxanthin and red betacyanin. They act as antioxidants and counteract biological molecule oxidation. Betalains are extensively used in desserts, confectioneries, dry mixes, dairy and meat products like modern food industries (Azeredo 2009).

Carotenoid pigment is found in extensive colored FV like peach, papaya, citrus fruits, green leafy vegetables, carrot, spinach, squash/pumpkin, and more. Different chemical structures of carotenoid are lycopene, carotene, cryptoxanthin, lutein, zeaxanthin, astaxanthin, and fucoxanthin having different functions like performing as pro-vitamin A, and antioxidant. However, carotenoids are used commercially in the feed and food industries as additives, supplements, colorants, and in cosmetic and pharmaceutical industries for nutraceuticals purposes (Jaswir et al. 2011).

A broad array of FVWs such as pea pod powder, fruit pulp, taro leaves, grape waste, okra, soya, and green gram waste are computed as prospective sources of mineral, carbon, and nitrogen to produce microbial pigments (Panesar et al. 2015). Microbial pigments are produced from bacteria, yeasts, mold, and algae by fermentation processes (solid-state or submerged fermentation). However, the amount of exploitation of countless nutrients and production of pigment may vary depending on the fermentation process and organism used. This kind of pigments has functions in the dairy, textile, food, and pharmaceutical industries (Panesar et al. 2015). Some pigments have abilities to fight against protozoal, bacteria, fungi, and are inflammatory and cytotoxic. The pigments play a vital role in upholding optical health and melanins are incorporated in sunscreen creams to guard the skin from ultraviolet radiation (Soliev et al. 2011). Microorganisms like *Serratia marcescens, Penicillium purpurogneum, Monascus* sp. produce red pigment; *Rhodotorula rubra, Monascus* sp., *Bacillus subtilis, Fusarium* sp. produce yellow pigment; *Saccharomyces neoformans*, *Cryptococcus* sp. are black pigment producers, and so on (Panesar et al. 2015).

4.3 Flavoring Agent and Aromas

FVWs can also act as the source for the production of flavoring agents and aroma. Many natural flavoring agents are volatile compounds manufactured from litters using biological transformations. The demand for natural and familiar flavors like vanillin, strawberry flavor, pineapple flavor, etc., are increasing. Vanillin formed from vanillic acid gives vanilla flavor. This vanilla is extracted from *Vanilla planifolia* by microbial transformation, fermentation, and enzymatic reactions. The precursor of vanilla is ferulic acid that is present in pineapple peel, orange peel, pomegranate peel. Vanilla flavor is the leading flavor and vastly used in detergent, food, beverages, pharmaceutical, and cosmetic industries (Tilay et al. 2008; Sagar et al. 2018; Lun et al. 2014).

Furaneol is a critical flavor/aroma compound, developing a flavor of caramelized pineapple in fruits such as pineapples, strawberries, mangoes, raspberries, etc. It imparts fruity and strawberry flavor at low concentration, whereas at high concentration it gives caramel and burnt sugar flavor. Methyl ether is responsible for aroma (Pickenhagen et al. 1981).

Essential volatile oils can be obtained from FVWs like orange peels, citrus peel, lemon peels, fruit seeds, garlic residues, thyme remains, oregano waste, clove residues, basil remainders, cinnamon rests, coriander leftover, ginger coverings, rosemary residues, and peppermint remains. The numerous volatile compounds are existent in the essential oil that retain flavoring and antimicrobial properties (Kalemba and Kunicka 2003). The utmost volatile compounds are alcohols, organic sulfur compounds, terpenoids, and aldehydes (Berger 2007). These essential oils are added in producing fragrances, bath products, cosmetics, household cleaning products, and flavoring of drink and food (Berger 2007). For instance; essential oils extracted from oranges have medicinal values, so they are supplemented as a constituent in gastric, purgative, and flatus-relieving preparations and tea formulations. Additionally, orange oil is applicable in remedying piles, slipping or falling of rectum and uterus, and diarrhea. D-limonene present in lemon improves immunity, pledges irregular moods, stimulates, boosts and activates mind and body, and cares skin by reducing wrinkles (Wadhwa et al. 2013; Berger 2007).

4.4 Dietary Fiber

Nowadays, people are being more health concerned for a healthy lifestyle and are more interested in having fruits rich in minerals, bioactive compounds, dietary fibers, and low in calories, sodium, and fats in their food. Dietary fibers are the indigestible carbohydrates present in plant cell walls and show central responsibilities in human diet together with health (Palafox-Carlos et al. 2011). Plant carbohydrate polymers and other non-carbohydrate components like pectin, hemicellulose, hemicellulose, waxes, polyphenols, resistant protein are dietary fiber (Elleuch et al. 2011). FVWs and agro-industrial by-products are high in fibers thus used as food supplements (Kowalska et al. 2017). Intake of dietary fiber reduces obesity, diabetes, cardiovascular diseases, hyperlipidemia, hypercholesterolemia, and hyperglycemia (Mann and Cummings 2009). Dietary fiber helps in the absorption of antioxidants like carotenoids and phenolic compounds. Dietary fiber also regulates digestion, absorption, and metabolism of nutrients. In addition, dietary fiber increases the fecal bulk, excites colonic fermentation, lowers insulin and cholesterol levels. Dietary fiber serves as food additives and delivers commercial profits to the pharmaceutical, food, and cosmetic industries (Elleuch et al. 2011; Kowalska et al. 2017). Dietary fiber has good water and oil holding capacity, emulsifying or/and gel-forming capacity, and swelling capacity so that it helps in lowering cholesterol, modifying the viscosity of intestinal contents, and forming gel with bile in the intestine (Palafox-Carlos et al. 2011; Elleuch et al. 2011; Ayala-Zavala et al. 2011). The addition of dietary fibers aid to modify the stickiness, consistency, self-life, and sensual characters of the foodstuffs like bakery products, dairy, meats, jams, soups, etc. However, the addition of fiber must be in the appropriate percentage otherwise it may produce detrimental changes in shade, flavor, and quality of foods (Elleuch et al. 2011). In bakery products, dietary fibers prolong the freshness, retain water, loaf volume, and flexibility thereby enhance digestion. Similarly, in dairy products like ice cream, the addition of fiber develops texture and managing properties by hampering crystal progression while storing (Elleuch et al. 2011; Ayala-Zavala et al. 2011).

4.5 Organic Acids

Organic acids have weak acidic properties and are produced from various organic matter by microbial processing. Those organic acids are branded building block chemicals and are used in food administering, gas and oil stimulation units, feedstuff and nutrition industries, drugs, esthetic and chemical industries, etc. Lactic acid, acetic acid, and citric acid are some organic acids which are manufactured from FVWs (Panda et al. 2016; Sauer et al. 2008). The selection of organism used and carbon source that enhances the growth of organism influence by-product formation and costs of the organic acids production procedure.

4.5.1 Citric Acid

Commercially important bio-product, citric acid acidifies and enhances flavor in food, medical and brew products. FVWs like apple pomace, cassava waste, pineapple waste, and maosmbi waste are used in citric acid production (Couto 2008). Citric acid can be manufactured either by submerged or solid-state fermentations utilizing various molds, yeasts, and bacteria. Of total citric acid produced, approximately 99% is through microbial procedures. Most popularly known citric acid-producing microbes are *Yarrowia lipolytica, Candida tropicalis, C. catenula*, *C. guilliermondii*, *Aspergillus niger*, and *A. wentii* (Max et al. 2010).

4.5.2 Acetic Acid

Acetic acid can be produced from FVWs. It is most commonly used as vinegar in almost all countries although the concentration of acetic acid varies in vinegar. The vinegar contains 4.1–12.3% of acetic acid in Canada produced vinegar (Panda et al. 2016). Acetic acid bacteria family includes *Endobacter, Acetobacter, Gluconobacter, Acidomonas, Bombella, Commensalibacter, Gluconacetobacter,* etc. For vinegar production, *Acetobacter, Gluconacetobacter, Gluconobacter*, and *Acidomonas* are recommended because they can highly oxidize sugar, sugar alcohol, and ethanol into acetic acid. Those bacteria are unaffected by acetic acid produced in fermentation media (Gomes et al. 2018).

4.5.3 Lactic Acid

Lactic acid is a high-value organic acid, commonly being expended in beautifying, food, leather tanning, and pharmaceutical industries. About 70% of lactic acid produced is consumed in yogurts and cheese-producing industries as acidulant and preservative. Lactic acid acts as a precursor for synthesizing polylactic acid, biodegradable composites in bioplastic production. Polymers of lactic acid are biodegradable, biocompatible, and have moisturizing, antimicrobial, rejuvenating, emulsifying properties. Thus, lactic acid has the potential to be used in various industries (Martinez et al. 2013). Bio-production of this acid is aided by various microorganisms using no cost or less cost substrate like fruits vegetables by-products and FVWs. Microorganisms including *Bacillus sp., Rhizopus sp., Saccharomyces cerevisiae, Kluyveromyces lactis, Pichia stipites, Lactobacillus casei, L. delbrueckii*, *L. plantarum,* etc., are lactic acid producers. FVWs like green peas remains, sweet corn waste, mango and orange residues, cassava residue, and potato peel can be used as low-cost substrates to produce lactic acid (Sagar et al. 2018; Martinez et al. 2013; Kong et al. 2019).

4.6 Bioenergy

The decrease in fossil resources and feedstocks, the ecological problems associated with greenhouse gas emissions, and also the increase in oil price are forcing to search for alternative resources for the production of transport fuels, energy, and compounds. In such cases, organic wastes and their intrinsic chemical complication are possible to be utilized as important resources for the generation of bioenergy like hydrogen, ethanol, and biodiesel. The feedstock, i.e., FVWs undergo changes during various fermentation processes before production of final bioenergy (Uçkun-Kiran et al. 2014; Sanders et al. 2007).

4.6.1 Bioethanol

Bioethanol commonly known as ethyl alcohol is a colorless liquid, decomposable, less toxic, and is used to power automobiles. Bioethanol can be produced from fermentable sugars like glucose, sucrose, etc., of plant sources (fruits and vegetable wastes) using microorganisms. Bioethanol produced from plant sources is CO_2-neutral because CO_2 is released while combustion of bioethanol is equal to the CO_2 absorbed by the plant during the growing phase (Chin and H'ng 2013). One of the most common and well-known bioprocesses for bioethanol production is yeast-catalyzed production method. Bioethanol production from wastes comprises steps such as biomass pretreatment and saccharification followed by fermentation of sugars. Different researches have been performed by using different FVWs like potato peel, apple pomace, apple waste, banana peel, banana waste, pineapple waste, soybean litter, and soybean molasses for bioethanol production using *Saccharomyces cerevisiae.* Mushimiyimana and Tallapragada also used agro-waste including peel of carrot, onion, sugar beet, and potato to produce bioethanol. In this process, *Penicillium* sp. and *Saccharomyces cerevisiae* are used for hydrolysis and fermentation to produce bioethanol, respectively (Mushimiyimana and Tallapragada 2016). Ingale and friends synthesized bioethanol from banana discards after pre-treating with *Aspergillus ellipticus* and *A. fumigatus* (Ingale et al. 2014). Bioethanol is consumed in fuel industries, pharmaceuticals, cosmetics, beverages, and chemical industries. It has been used as adhesive in dyes and paints, raw materials for plastics, preservative, solvent for spirits industries, disinfectant, bleaching agent, and cleaning agent, etc. (Chin and H'ng 2013).

4.6.2 Biohydrogen

Biohydrogen is universally recognized as complementary to fossil fuels due to its non-polluting feature, less costly, and renewable source. Hydrogen gas includes 2.75 times greater energy yield than hydrocarbon fuels and it is carbon neutral. This can be considered as a clean fuel and energy carrier without CO_2 releases and can be easily operated in generating electricity (Kapdan and Kargi 2006). With the development of sustainable and minimization of waste policy, biohydrogen production is realized from renewable sources, also known as green technology. Hydrogen can be made by different processes; electrolysis of water, biological processes, and thermocatalytic reformation of hydrogen-rich organic compounds (Kapdan and Kargi 2006). Biological processes for hydrogen generation using microorganisms is an exciting approach and includes different methods including direct biophotolysis, indirect biophotolysis, dark fermentation, and photo fermentation. Biophotolysis refers to breaking water molecules by microbes like green microalgae and cyanobacteria into hydrogen and oxygen in presence of sunlight, whereas fermentation process refers to the production of biohydrogen by converting organic compounds as an energy source by microbes in the absence or presence of light (Levin et al. 2004; Rahman et al. 2016). Biohydrogen is produced as a secondary outcome during anaerobic alteration of organic wastes, whereas in photosynthetic processes microorganisms use carbon dioxide and water for hydrogen production (Levin et al. 2004). Different wastes like potato waste, pumpkin waste, fennel waste, olive pomace, leafy vegetables like cabbage, water celery, cauliflower, etc., can be a substrate for biohydrogen production (Ghimire et al. 2015; Lee et al. 2010). Some biohydrogen producers are *Clostridium butyricum, Bacillus sp., Escherichia coli, Rhodobacter sphaeroides, Rhodopseudomonas palustris, R. faecalis, Rhodospirillum rubrum*, etc. (Rahman et al. 2016). The principal application of biohydrogen is utilization as a fuel cell for generating electricity, however, during the production of biohydrogen other gas such as ammonia, methane, hydrogen sulfite may be produced (Levin et al. 2004; Rahman et al. 2016) which can be used for advantages.

4.6.3 Biomethane

Biomethane is a cheap form of bioenergy which can be produced from anaerobic digestion of biogenic wastes by different microbes. The practice of vegetable waste to generate biogas is environmentally friendly and resolves the residual disposal problem, air and water pollution, soil contamination, and lowers reliance on wood fuel. During anaerobic digestion, the acidogenic microbes are responsible to produce acetate, carbon dioxide, and hydrogen. This produced hydrogen along with acetate is digested by methanogens into water and methane. The charging rates of biodegradable organic FVWs should be proper to produce methane. For example, if loading of organic waste is high, the digestion by acidogenic microbes increases, while methanogenic microbes are unable to increase which results in the termination of methane production. Biomethane production involves hydrolysis, methanogenesis, and acidogenesis that are completed by a sequence of microbial interactions. However, the products differ with the type of bacteria involved (Singh et al. 2012). A previous study used vegetable waste like salad leaves, potato peelings, green peas, and carrots remains in a number of phase transitioning reactors and a focal reactor to produce biomethane (Raynal et al. 1998). Organic waste influences excessive production of methane and processed slurry formation. This processed suspension can be applied in conditioning soil or biofertilizer (Singh et al. 2012).

4.6.4 Biodiesel

Biodiesel is a renewable and clean-burning liquid biofuel which consists of low aliphatic alcohols and esters of alkyl groups having high fatty acids. Biodiesel can be considered as "carbon neutral" because this biofuel produces no net output of carbon dioxide. In addition, biodiesel is inexhaustible and perishable energy which reduces very fast (4×) than fossil fuel, has greasing assets that reduce engine wear, and is secure for storing and management due to low explosiveness and a high flash point of 100–170 °C (Ramirez-Arias et al. 2018). Transesterification is a commonly applied procedure of producing biodiesel, requires only low temperature and pressure, and produces 98% conversion yield (Muniraj et al. 2015). However, supercritical fluid extraction methods can also be applied to extract biodiesel from oilseed (Lee et al. 2010). In the transesterification process, triglyceride reacts with alcohol to form biodiesel and crude glycerol. Fruits and vegetable wastes rich in lipids or oil such as rapeseed, palm, soybean, and canola are used in biodiesel manufacture (Lee et al. 2010; Muniraj et al. 2015). The choice of feedstocks plays a critical role in regulating the cost of diesel (Singh et al. 2012). Vegetable oils are countered with ethanol in the existence of catalysts in biodiesel production (Stamenkovic et al. 2011). Approximately 100% of the yield of biodiesel was obtained by Lee et al. from canola oil waste employing supercritical fluid extraction methods. Biodiesel can also be recovered from microbial oils/lipids thus, oleaginous microorganisms (capable of accumulating lipids) including algae, yeast, and fungi can be probable feedstocks for manufacturing biodiesel (Muniraj et al. 2015; Zhang et al. 2016). In the study of Surendra et al., larvae of *Hermetia illucens* were used in efficient organic waste management, and the larvae were cultivated on food trash to yield fat plus prepupae rich in protein. These black soldier fly prepupae derived oil was converted into high-quality biodiesel (Surendra et al. 2016).

4.7 Bioplastics

Bioplastics are the biopolymers as plastic material having mechanical endurance, easy processability, chemical apathy, weightlessness, flexibility, and produced from renewable sources. Bioplastics are biodegradable and can be synthesized from FVWs. Biopolymers have obviously prevailing starch, cellulose, protein, lignin, natural rubber-like molecules. The main important component of bioplastic is polyesters and the biodegradable polyesters are in different commercial forms. The commercial biodegradable polyesters are as follows; polybutylene succinate adipate (PBSA), polylactic acid (PLA), polyhydroxyalkanoate (PHA), polyglycolic acid (PGA), polybutylene succinate (PBS), aliphatic–aromatic copolyesters (AAC), polybutylene adipate/terephthalate (PBAT), and polymethylene adipate/terephthalate (PTMAT). Among these, PLA and PHA are the most important synthetic bioplastics (de Moura et al. 2017; Esparza et al. 2020). PLA can be obtained from the processing of renewable carbohydrate sources like corn into dextrose and further followed by bacterial fermentation in which dextrose is converted into lactic acid. PLA is biodegradable, decomposing to give H_2O, CO_2, and humus (Drumright et al. 2000). Bacteria that are employed in the production of PLA belongs to *Lactobacillus* genus such as *L. acidophilus, L. amylophilus, L. casei, L. maltaromicus, L. salivarius, L. delbrueckii, L. bavaricus, and L. jensenii* (Nampoothiri et al. 2010). FVWs like sugarcane and cassava bagasse, potato wastes, tapioca, corn stover, carrot waste, beet syrup, sweet sorghum, etc., may be used for PLA invention. PLA is applied in releasing controlled drugs, fixing bone fixation, composites implantation, packaging, coating paper, releasing sustained pesticides and fertilizers, etc. (Nampoothiri et al. 2010; Castro-Aguirre et al. 2016).

PHAs are the second most essential synthetic bioplastics after PLA (Esparza et al. 2020). PHAs are polyesters that are synthesized from the polymerization of various hydroxy alkanoic acids by microorganisms. These microorganisms accumulate this biopolymer in the cytoplasm as stored energy. Some bacteria and filamentous fungi can produce enzymes to decompose PHAs. Pomace from fruits like apricot, cherries, grapes can be a carbon source and recycled culinary oil as a precursor for PHAs production (Follonier et al. 2014). PHA-producing microbes are *Ralstonia eutropha, Pseudomonas oleovorans, Chromatium vinosum, Thiocapsapfennigii*, etc., and these microbes have PHA synthase enzyme. Bioplastic has a wide range of applications like in manufacturing latex paints, in medical application with tissue engineering, to obtain enantiomeric pure hydroxyalkanoic acid, etc. (Steinbüchel 2001).

4.8 Exopolysaccharides (EPS)

EPS are polysaccharides secreted by microorganisms outside the cell or in the medium throughout the growth phase and occur as capsule or slime. EPS varies with exceptional physical and chemical characteristics. EPS manufactured by lactic acid bacteria are considered harmless and used as food additives or as functional food ingredients (de Vuyst et al. 2001). However, few EPS can provide infectious and immunogenicity which differs in different species of microorganisms (Weiner et al. 1995). EPS can be homopolysaccharides like D-fructose and D-glucose having indistinguishable monosaccharide units and heteropolysaccharides consisting of different monosaccharides in distinctive proportions (de Vuyst et al. 2001). EPS can be used as a corporal barrier, in cell/cell identification and cooperation, a rejoinder to conservational stress, and in biofilm expansion/adherence (Weiner et al. 1995). Some of the microbial EPS advantageous in industries are dextran, xanthan, pullulan, and gellan secreted by *Leuconostoc mesenteroides, Xanthomonas campestris,* and *Sphingomonas paucimobilis,* respectively. Microbial EPS are particularly used to improve the consistency, rheology, and flavoring properties of dairy products that increase both wellbeing and financial benefits (Esparza et al. 2020; de Vuyst et al. 2001). The Food and Drug Authority approved xanthan as a food additive biopolymer after that the insistence of xanthan has been increasing. Xanthan is used in cosmetics, pharmaceutical, textile, petroleum, and especially the food industry (Esparza et al. 2020). Pullulan is a decomposable polysaccharide found in the culture medium of *Aureobasidium* *pullulans*. This biopolymer is applied as covering in food, as a low-fat constituent, as a prebiotic, as surface-active and stabilizing agent, as denture adhesives, as drug transporter, vaccinations, and capsule coating, etc. (Esparza et al. 2020; Prajapati et al. 2013). Generally, synthesizing pullulan, xanthan like exopolysaccharides are relatively expensive because glucose and/or saccharose are used as the solitary carbon source for the growth of microorganisms. However, carbon source from cassava waste, potato waste, coconut waste, sugar cane waste, sugar beet waste, maize waste, orange waste, asparagus waste, etc., can be expended so as to reduce the production costs which further reduce the disposal problem and encourage the re-use of waste (Esparza et al. 2020).

Heteropolysaccharides are long-chain polymers when suspended or dispersed in water, display gelling characteristics. This thickening property is essential in the formulation of some food products. Such polymers are also applied for stabilization, emulsification, suspension of particulates, crystallization control, encapsulation, film formation, and syneresis inhibition (Vendruscolo et al. 2008). Heteropolysaccharides producing bacteria are *Lactobacillus* sp., *Streptococcus thermophilus, Lactobacillus lactis, L. helveticus, L. delbrueckii,* etc. Different wastes like apple waste, soy waste, etc., are utilized by microorganisms in producing heteropolysaccharides (de Vuyst et al. 2001). The most common natural heteropolysaccharide found in FV peels and used in different industries for the production of various products is pectin (Tan et al. 2018). Pectin heteropolysaccharide is a normal food element for jellies, jams, and marmalades, for treating diarrhea with calcium salts due to its gentle decline in the intestine, has prebiotic effect stimulating belly health by regulatory microbial inhabitants (Tan et al. 2018). Pectin produced from different sources varies in properties, for example, apple pectin solidifies superiorly to citrus pectin. However, apple pectin has inferior properties to mango pectin (Adi et al. 2019). Thus, heteropolysaccharides like pectin can be produced from organic wastes so that it assists in declining the production cost, pollution, and environmental cleanliness.

4.9 Single-Cell Protein (SCP)

SCP is a protein that originated from microorganisms such as algae, bacteria, fungi, and yeast. Those microorganisms can utilize various carbon sources for SCP synthesis. For human consumption, SCP is commonly produced from filamentous fungi and yeast. However, bacterial SCP is generally used in feed industries (Ritala et al. 2017). Different FVWs can be used as cheap or no cost carbon source for the growth of microorganisms and SCP production (Najafpour 2007; Mondal et al. 2012). These substrates include pineapple waste, banana peels, pomegranate peel, watermelon waste, beet pulp, papaya waste, corn cob, soybean waste, orange peels, cucumber peels, etc. SCP producing expertise is an appropriate practice for transforming unwanted materials into useful protein. *Aspergillus oryzae, A. flavus, A. niger, Fusarium semitectum, Rhizopus oligosporus, Saccharomyces cerevisiae, Trichoderma harzianum, T. reesei, Penicillium javanicum, Kluyveromyces marxianus*, etc., can be used for SCP production (Malav et al. 2017). The production of SCP relates to the type of substrate availability, constituents present in media (Mondal et al. 2012), and environmental conditions (Reihani and Khosravi-Darani 2018). There are few steps for SCP production. General steps are (a) preparation of culture media, (b) cultivation, (c) extraction and intensifying SCP, and (d) final processing of SCP. SCP initially was popular during war times in human nutrition, when conventional protein sources were not sufficient. It is again becoming important to fulfill the protein demands of an increasing population, and can also be used in livestock feed as a protein source. Algal SCP offers omega-3 fatty acids, vitamins, carotenoids along with protein, and thus SCP is used as food supplements. Production of SCP utilizes methane as a carbon source and helps to reduce greenhouse gas emission as well (Ritala et al. 2017).

5 Conclusion and Future Prospects

The increase in population, as well as fruits and vegetable consumption with increase in nutrition awareness, is generating a huge amount of FV wastes. However, some nutrients and compounds existent in FV wastes can be potential sources for feeding animals, making organic fertilizer, or for producing value-added products. On the whole, it can be concluded that FV wastes can be reused as cheap or no cost substrate in yielding various value-adding products like biologically active compounds, enzymes, pigments, bioenergy, etc. Those valuable compounds are helpful to lessen the overall production cost. For example, producing enzymes or biopolymer from fruits processing waste and essential oils from fruit peels are value-adding products that may reduce the entire production cost. In addition, appropriate utilization of food sources minimizes the production of food trashes and disposal problems and also helps in solving hunger problems of increasing population. Moreover, the sustainable utilization of resources from FVWs can reduce greenhouse gas emission, and finally, waste can be converted into wealth.

With the adoption of advanced techniques such as protein and/or genetic engineering, molecular biology, and bioinformatics the researchers can generate improved microbial strains to consume FVWs and prevent losing valuable compounds from wastes. Thus, effort has to be made in the development and adoption of efficient microbial strains, for example, plethora of enzyme production in heterologous hosts and their reformation by protein engineering or chemical resources can achieve dynamic and effective enzymes. Such strains can be utilized in the commercial production of different value-added products from wastes by reducing the investment cost and minimizing the waste production.

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