Valorization of Agri-Food Wastes and By-Products

Recent Trends, Innovations, and Sustainability Challenges

Edited by **Rajeev Bhat**

Chapter 7

Fruit and vegetable by-products: novel ingredients for a sustainable society

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7.1 Introduction

Fruits and vegetables are a rich source of nutrients, consumed in large amounts as food. By-products of fruits and vegetables refer to those secondary products obtained from the primary source during the manufacturing process and include peels, seeds, leaves, residual pulp, stems, stones, and discarded pieces, etc. They are found to possess potent bioactive molecules, healthy nutrients or nutraceuticals, and functional foods. Various parts of fruits and vegetables are enriched with bioactive molecules, such as phenolic compounds, carotenoids, and vitamins, that fall under the category of primary and secondary metabolites. Furthermore, the presence of such bioactives in the by-products of those fruits and vegetables has a higher biological impact, like antioxidant and antimicrobial properties, than the edible parts. Hence, a gradual trend has been observed toward the consumption of such by-products with extra value.

Fruits and vegetables have an undifferentiated role in human diet and lifestyle. As a result, the demands for such food commodities have increased due to the growing global population and changing dietary practices (Vilarino, Carol Franco, & Quarrington, 2017). This is reflected in the gross world production of fruits and vegetables. As per the report of the FAO, in 2017, citrus fruits, bananas, apples, grapes, mangoes, mangosteens, guavas, and pineapples were produced in quantities of 124.73 million metric tons (MMT), 114.08 MMT, 84.63 MMT, 74.49 MMT, 45.22 MMT, 41.00 MMT, 3.60 MMT and 25.43 MMT, respectively. Over recent decades, there has been a gradual increase in the demand for fruits and vegetables that has led to continuous production increases. In 2017, demand was about 900 million tons of fruits and over 1000 million tons of vegetables (http://www.fao.org/faostat/en/#data). The fruits which have been prominently produced in the last few years include various species of citrus, watermelon, banana, apple, grape, and mango, etc. On the other hand, the most popular vegetables were potatoes, tomatoes, onions, cucumbers, cabbages, etc. Despite the huge production, the global demand for fruits and vegetables remains high (GBD 2017 Diet Collaborators, 2019) and the future outlook in this area, especially by-products utilization, is yet to be explored. In this contrast, the generation of food waste even, at an individual level, is alarming. A general estimate suggested that globally 1.94−3.89 quintals of food waste or loss (for various reasons) were found in a single year (Corrado & Sala, 2018). It is pertinent to point out that food waste should be a concern for all of society in terms of the social, environmental, and economic affects (Corrado & Sala, 2018). Among all food waste produced, waste incurred due to fruits and vegetables stands has a high wastage rate, where almost half of the harvested products are wasted each year. In a developing country like India there are 23 million tons of food cereals, 12 million tons of fruits, and 21 million tons of vegetables wasted every year because of proper infrastructure and lack of cold chain facilities. As in India, one-third of global food production, an estimated nearly 1.3 billion metric tons, is wasted (FAO, 2014), with fruit and vegetables representing about 60% of this total. Most of the losses happen during the postharvest period before reaching the consumers. The postharvest loses in developing countries like the United States are estimated at about 2%−23% (on average 12%) depending upon the commodity and in the UK it is around 9%. The amount of fruit and vegetables waste has been revealed in various countries including China, India, Philippines, and United States etc. together nearly around 55 million metric tons in a year during processing, packaging, distribution, and

Valorization of Agri-Food Wastes and By-Products. DOI: https://doi.org/10.1016/B978-0-12-824044-1.00006-4

consumption (FAO, 2014). Such huge waste can be minimized by identifying the global appropriate regions where lowest need of extra food supply. By doing this the global practice, the fruit and vegetable wastage can be minimized.

The current trend shows that fruit-processing industries annually contribute nearly 600 million tons of fruits waste globally (Banerjee et al., 2017). This includes the inedible parts of different fruits like bananas (35%), pineapples (46%), grapefruit (30%), citrus (25%−35%), apples (12%), and watermelon (48%), and vegetables like cauliflower and broccoli (43%), carrots and turnips (20%), and garlic (22%) (De Laurentiis, Corrado, & Sala, 2018). On the basis of the characteristics of the waste materials generated, they can be classified as organic or inorganic waste. The current focus is on organic waste, which generally is obtained from fruits and vegetables as by-products, and also from other living sources. Recently, the utilization of waste by-products has gained attention worldwide for the production of food additives or high nutritional value supplements of high value. These may serve as a potential source for polyphenolics, sugars, minerals, organic acids, dietary fibers, etc. Polyphenols have been reported as having numerous biological activities including cardioprotective, antitumoral, antibacterial, antiviral, and antimutagenic. However, despite this, the utilization of by-products remains limited due to the insufficient knowledge of their nutritional and valuable economic qualities (Peiretti & Gai, 2015). Fruit and vegetable by-products generally have a high water content, which makes them very prone to enzymatic hydrolysis and microbial contamination as a result of faster decay. Some by-products are utilized in the production of biogas, biofertilizer, and are also used in animal husbandry as animal processed feed, etc. In addition to their existing uses, value addition can be done to fruit and vegetable by-products by converting them into various essential oils, edible oils, enzymes, pigments, single-cell proteins, biodegradable films, etc. However, this chapter focuses solely on the by-products obtained from fruits and vegetables and their reliable sustainable production and utilization in different areas. It not only discusses the current status of fruit and vegetable by-product utilization but also widens the technical prospects of such by-product preparation and sustainability, which could help a broader community of researchers and industrialists to identify new inventions and market supplies for these by-products.

7.2 Bioactive molecules from fruit and vegetable by-products

The bioactive phytomolecules, especially phenolics and dietary fiber, are the most prominent in fruits and vegetables. These phytoconstituents are found to be mainly responsible for health benefits due to their antioxidant potentials (Shahidi & Ambigaipalan, 2015). In addition to their antioxidant potentials, they also regulate transcriptional gene and enzyme modulation in the production of inflammation mediators. In general, fruit and vegetable by-products have huge potential for recycling because are a natural source of bioactive compounds. This includes simple sugars like glucose and fructose, carbohydrates, polysaccharides, pectin, fiber, and valuable bioactive molecules like phenolic acids, carotenoids, tocopherols, flavonoids, vitamins, and aromatic compounds (Ferrentino et al., 2018).

7.2.1 Polyphenols

Polyphenols are a group of chemicals or micronutrients found in plants. They contains more than one phenol unit as a structural building blocks per molecule. Fruit and vegetable by-products are great sources of polyphenols, for example, 100 g of sweet cherry contains 274 mg polyphenolics. In fact, they can be found as a precursor of several by-products of fruit and vegetables. The largest group of phytobiomolecules is polyphenols, with distinct structural diversity and they are representative of numerous types of chemicals with a minimum of one aromatic ring in their basic structure and they also contain one or more hydroxyl groups. On the basis of their diverse structures, they are classified as hydroxybenzoic, hydroxycinnamic acids, anthocyanins, proanthocyanidins, flavonols, flavones, flavanols, flavanones, isoflavones, stilbenes, and lignans. These groups of chemicals are present in various concentrations and combinations with other phytomolecules in fruits and vegetables as well as in their by-products.

7.2.1.1 Biomedical impacts of phenolic compounds

The role of polyphenols in the prevention of oxidative stress associated with cardiac disease, cancer, diabetes (type II), neurodegenerative diseases, and osteoporosis is well defined due to their redox potentials. Numerous phenolic compounds have also shown remarkable potential in terms of their inhibitory effects on obesity (catechin, epicatechin, epigallocatechin, etc.) and also molecular signaling mechanisms in the cell. In addition, carotenoids have also displayed antioxidant potentials by suppressing the free radical damage in cellular integration, which was also reported as lowering the risks of certain types of cancers, improvisation of the immune system, prevention of cataract formation, and even coronary heart diseases and stroke, furthermore they are the best sustainable source of retinol (Hang, Christopher, & Quan, 2018).

7.2.2 The terpenes

Terpenes are simple unsaturated hydrocarbons mainly found in essential oils or plant resins and are scientifically proven to possess potent antioxidant property. They belong to the largest class of secondary metabolites derived by enzymatic reactions of primary metabolites. Chemically, they possess five-carbon isoprene units assembled in numerous ways. Distinct classes of terpene are categorized, including carotenoids, limonoids, saponins, and 6-chromanols derivatives.

7.2.2.1 Carotenoids

Fruits and vegetable by-products also contain extra-nutritional lipophilic phytoconstituents called carotenoids. So far, approximately 600 carotenoids of natural origin have been identified with diverse biological functions. However, unfortunately, only few of them (approximately 50 carotenoids) are found in the human diet (Tan & Norhaizan, 2019). Various forms of such carotenoids include α-carotene, β-carotenes, lutein, zeaxanthin, etc. Orange carrot, orange sweet potato, mangoes, nectarines, and green leafy vegetables are rich sources of β-carotene and lutein. The yellow phytoconstituents, that is, zeaxanthin, and xanthophyll carotenoids are commonly found in yellow foods such as orange juice, honeydew, yellow squash, yellow corn, yellow carrots, and orange peppers, but rarely reported in green leafy vegetables. Another important bioactive from the same category is lycopene, which is normally found in watermelon, tomatoes, pink grapefruit, etc. (Padayachee, Day, Howell, & Gidley, 2017; Rao & Rao, 2007). Carotenoids are known for their intensified relationship with prevention of aging process. Recent studies revealed that carotenoids enable the interruption of free radical propagation as a result of lowering oxidative stress. Hence carotenoids act as a potential intervention in the aging process (Tan & Norhaizan, 2019).

7.2.2.2 Limonoids

These are highly oxygenated and modified terpenoids, also known as tetranortriterpenoids. They possess a prototypical structure either containing or derived from a precursor with a 4,4,8-trimethyl-17-furanylsteroid skeleton. Limonoids are generally found in citrus fruit peels (responsible for the delayed bitterness of juice). Limonoids have shown numerous biological activities, which include insecticidal, and antifeeding, insect growth-regulating activity. They also exhibit potential antitumor, antioxidative, antiinflammatory, antineurological, immunomodulatory, and pharmacological activities (Shi et al., 2020). Hundreds of limonoids have been isolated and identified from plant sources (especially from Meliaceae and Rutaceae families). To date, limonoid aglycones (about 55) and limonoid glycosides (about 18) have been identified from citrus fruits (Shi et al., 2020). Currently, the focus is concentrated on genetic engineering to maximize the formation of limonoid glucosides for reducing limonoid bitterness in citrus juice and products to counter the problem of bitterness.

7.2.2.3 Saponins

These are a group of strongly bitter-tasting surface-active phytoconstituent consisting of steroid or tritepenoid aglycone moiety (sapogenin) structures linked to one or more oligosaccharides. They are found in beans, quinoa seeds, alfalfa, and legumes. Sapogenols or sapogenins are widely distributed plant glucosides. They are further categorized as anticipins, consisting of an aglycone unit, that is, triterpenoid saponins and steroidal saponins, structurally consisting of one or more carbohydrate moieties. Anticipins have been isolated and identified in over 100 plant families. More than 11 different class of phytochemicals, that is, triterpenoid saponins (like cycloartanes, cucurbitanes, tirucallanes, hopanes, lupanes, oleananes, taraxasteranes, ursanes, etc.) and steroidal saponins (spirostanols, furostanols, alkaloids, etc.) showed bioactivity. The bioactivity of saponins include cytotoxic, immunomodulatory, hepatoprotective, antidiabetic, hypolipidemic, antiosteoporosis, antiviral, antifungal, anthelmintic, etc.

7.2.2.4 6-Chromanols derivatives

Chromanols derivatives are formed by cyclization of substituted 1,4-benzoquinones. |Meanwhile 6-hydroxy-chromanols are derived from a 2-methyl-3,4-dihydro-2*H*-chromen-6-ol structure. Vitamin E is a complex mixture of tocotrienols and tocopherols. It comes under the series of 6-chromanol derivatives, which is substituted by a saturated or partially saturated isoprenoid side chain and one to three methyl functional groups. It is abundantly found in palm oils, whole grain germ, leafy vegetables, and bran. Tocopherols and tocotrienols generally showed bioactivity in vertebrates and may act as anticancer, antidiabetic, antiinflammatory, antioxidant, immune-stimulatory, cardioprotective, neuroprotective, hepatoprotective, and nephroprotective molecules in living systems. In the 6-hydroxychromanol ring system, tocopherols are further divided into the most prominent vitamers, that is, α(5,7,8-trimethyl)-tocopherol, β(5,8- dimethyl)-tocopherol, γ(7,8-dimethyl)-tocopherol, and δ(8-methyl)-tocopherol, etc.

7.2.3 Biomedical impacts of carotenoids

Carotenoids act as a potent antioxidant with immunity-boosting potency. Due to their high reactivity toward singlet oxygen in the cellular membrane, they are referred to as membrane antioxidants. A diet enriched with carotenoids has a good impact in lowering the risk of certain clinical conditions including cancer, macular degeneration, cataracts, and heart disease. Limonoids act as a chemopreventive agent, whereas saponins obstruct the exponentiation of cancer cells by intrusive with their nucleic acid sequences. Tocotrienols are reported to inhibit breast cancer cell growth and tocopherols were found to have a beneficial effect on cardiac health (Aggarwal, Sundaram, Prasad, & Kannappan, 2010). Serum carotenoid concentrations are the indicative biomarker for dietary intake measurements in fruits and vegetables. However, different populations or individuals from these populations may show a high level of variability in dietary intake and serum carotenoid levels (Bohn et al., 2017; Rodriguez et al., 2018), which may be due to the various factors, for example, geographical availability, socioeconomic, and cultural effects.

7.2.4 Dietary fiber

Fruit and vegetable by-products are enriched with a high quantity of dietary fiber. For example, in 100 g of solid apple pomace, about 93.2 g is fiber. Fruit by-products are the main sources of pectin, peels are a source of cellulose and hemicellulose, and seed coats contain lignins (Banerjee et al., 2017). In the large bowel, carbohydrate degradation mainly yields short-chain fatty acids, for example, acetate, propionate, butyrate, etc., which have a positive impact on intestinal epithelium and gut system health (Verspreet et al., 2016). The biological actions of fiber derived from fruits and vegetables depend on their physicochemical characteristics. If these molecules are tightly arranged then they form highly stable crystalline fibers known as insoluble fibers, for example, cellulose. On the other hand, the irregularly configured and isolated fibers, such as pectins, are known as soluble fibers (Verspreet et al., 2016). Typically soluble fiber is present in a relatively dense particle form and strongly resists penetration by colonic microbiota, as a result, it disables the gut bacteria for the process of fermentation and enables bowel scouring, epithelial development in the colon, and bulky stool development (Padayachee et al., 2017). Later, fibers are soluble in the gastrointestinal fluid or swollen or dissolved in water to form viscous or gel solution and are readily fermented by the large intestinal microflora.

7.2.5 Biomedical impacts of dietary fiber

Dietary fibers are indigestible carbohydrates obtained from fruits, vegetables, and their by-products, which cannot be hydrolyzed by the influence of endogenous enzymes in the intestine. Due to this, they can be utilized by the gastrointestinal tract (GIT) microflora. Dietary fibers are basically a complex group of substances with diverse structural properties and impacts. Exopolysaccharides (EPS), extracellular polysaccharides which are secreted or attached to the walls of bacteria affecting adhesion by shielding cell surface, act as ligands. Dietary fiber significantly influences the metabolism by providing a cleansing action in the intestine. Dietary fiber significantly reduces the level of blood glucose (postprandial) and cholesterol (Gunness et al., 2016a). The gastrointestinal passage rate, digestive enzyme interaction, viscosity, etc. can be improved with the use of soluble dietary fiber (Gunness et al., 2016b; Padayachee et al., 2017).

7.2.6 Polysaccharides

Polysaccharides are characterized as a bio-macromolecule obtained from living organisms, structurally composed of homo- or hetero-monosaccharides and uronic acids closely connected with glycosidic linkages. The soluble and insoluble fibers also are made up of nonstarch polysaccharides. They are chemically complex carbohydrates consisting of large sugar molecules, for example, cellulose, starch, dextrin, etc. Pectin and pectic acid are other plant polysaccharides often present in the diet. Polysaccharides exhibit a wide range of bioactivities, for example, antioxidant, antitumor, antimicrobial, antiobesity, hypolipidemic, antidiabetic, and hepatoprotective. Vigorous scientific explorations have taken place into the development of novel products in cosmeceuticals, food, pharmaceuticals, petrochemicals, paper industries, etc. (Jung et al., 2017). They are widely used as biomaterials in hypoglycemic, antiosteoarthritic, and anticancer products in pharmaceuticals and medical areas.

7.2.6.1 Phytosterols

Phytosterols are a steroid-alcohol composed of a tetracyclic cyclopenta-α-phenanthrene ring. Structurally, phytosterols are similar to cholesterol, which acts on the intestine by lowering the absorption of cholesterol. Low systemic absorption is the basic characteristic of phytosterols which are present in healthy foods like fruits and vegetables. Phytosterols intake in the diet may reduce the risk of coronary heart disease in humans. Seed oils, soybean oil, rapeseed oil, olive oil, walnut oils, grapeseed oils, and peony seed oils are the best sources of phytosterols. Such vegetable oils are obtained using different oil-processing technologies. However, the content and composition of phytosterols is altered during the oil extraction process, and depends on the refining degree and source of raw materials. The conversion of testosterone to dehydroxy testosterone also is inhibited by phytosterols. They are also found in plants, free or esterified with fatty acids, steryl glycosides, and acylated glycosidal forms.

7.2.7 Biomedical impacts of phytosterols

Phytosterols have two principal biological functions, these are signaling molecules that activate steroids hormone receptors and becoming a component of the cell membrane that affects the flexibility of the membrane in living cells (Bot A., 2019). They also have been proved to have hypercholesterolemic, immunological, and antiatherosclerotic activities. They play an important role as immunomodulatory agents against the development of diseases generally increase in $CD3^{+}$ $CD4^{+}$ T cells relative to $CD3^{+}$ $CD8^{+}$ T cells. The antiinflammatory activity of phytosterols is due to the increased IL-4 cells in the body.

7.2.8 The organosulfurs

Organosulfur generally refers to those organic compounds that contain a sulfur (−SH) group in their structural skeleton. They provide glucosinolates, a pungent phytochemical with sulfur and nitrogen atoms. Glucosinolates play a crucial role in the human body by being converting into several biotransformation products like indole-3-carbinol, isothiocyanates, and thiosulfonates, etc. They are mainly found in the Cruciferae family, and horseradish, cabbage, broccoli, brussels sprouts, cauliflower, mustard seeds, turnip greens, etc. are popular sources of organosulfur. S-alk(en)yl-l-cysteine sulfoxides and S-methyl cysteine-l-sulfoxides are the two major organosulfurs in the Amaryllidaceae and Brassicaceae families (Goncharov N. et al., 2016).

7.2.9 Biomedical impact of organosulfur compounds

Organosulfur compounds are found in the form of S-alk(en)yl-l-cysteine sulfoxides and S-methyl cysteine-l-sulfoxide in fruit and vegetables, and are best known for their antioxidant, antiinflammatory, anticarcinogenic, and antiangiogenic effects. They also help in the breakdown of toxinogens and estrogenic toxic metabolites in the liver. Phase II detoxication is also assisted by organosulfur (thiosulfonates) which protect the development of carcinogens and even promote a favorable HDL:LDL ratio, lower blood pressure, and stimulate nonspecific immunity (Gupta P. et al., 2015).

7.2.10 Organic acids and plant amines

The organic acids, such as oxalic acid, cinnamic acid, caffeic acid, ferulic acid, gallic acid, salicylic acid, tannic acid, coumaric acid, and ellagic acid are found more commonly in fruit by-products than vegetables. These organic acids are also found in grains, herbs, and a few vegetables and some fruits. For instance, oxalic acid is found in spinach, tartaric acid in apricots and apples, cinnamic acid in aloe and cinnamon, salicylic acid in mint, ellagic acid in apples and grapes, etc. Plant amines are another class of plant chemicals containing nitrogen (−NH) as the key atom which plays a vital role in biological systems and are reported in vegetable by-products. They include both chlorophyll (spirulina, hydrilla) and plant enzymes (papain and bromelain).

7.2.11 Biomedical impact of organic acids and amines

An organic acid has powerful antioxidants, and antiinflammatory and liver detoxication agents. Ellagic acid has been noted for its anticarcinogenic, antimutagenic, and anticancer initiator activities. On the other hand, plant amines (chlorophyll) are well known for detoxifying carcinogens (heterocyclic amines, polycyclic hydrocarbons, aflatoxin, etc.). They are also known to possess antiinflammatory, antimutagenic, and antioxidant properties. Plant enzymes are useful in assisting digestion, injury resolution, and antiinflammatory and immune response enhancement.

7.3 Sustained valorization of fruits and vegetable by-products

Valorization of fruit by-products is urgently needed to maintain the balance in the environment in terms of waste management and economy of valuable fruit by-products. Some fruits are discussed below for their by-product utilization in different fields, such as, food, biotechnology, and pharmaceuticals. Proper knowledge of by-products and the proper valorization techniques will make a huge difference in the current situation of fruit wastage and economic burden.

7.3.1 Apple by-products

Malus domestica, commonly known as the apple, is consumed worldwide as a nutrition-rich fruit. As per the current data, the global production of apples was around 68,700 metric tons in 2019 (https://www.statista.com/statistics/279555/global-top-apple-producing-countries/).
Phenolic compounds like quercetin, numerous derivatives of naringenin, catechin, epicatechin, and phloridzin are found in significant amounts in apple. In addition, various phenolic acids like ferulic, p-coumaric, caffeic, chlorogenic, and gallic acid are also present. Moreover, they

also contain sugar alcohols, various vitamins, and amino acids (Du et al., 2019; Maragò, Michelozzi, Calamai, Camangi, & Sebastiani, 2016; Pires et al., 2018). More than two-thirds of global production of apples is consumed as fresh fruit and the remaining third is utilized in industrial processes for the preparation of juices and cider, and frozen and dried processed products. The major processed waste or by-product is apple pomace, which is generally formed after making juice. About 95% of apple pomace contains peels or flesh and the remaining 2%–5% is seeds and stem. Various by-products can be isolated from apple pomace, including pectins (5%–10%), cellulose (7%–40%), hemicelluloses (4%–25%), and lignins (15%–25%), and some secondary soluble metabolites such as tannins, resins, reducing sugars, and pigments (Zhu, Du, Zheng, & Li, 2015).

7.3.1.1 Sustainable applications of apple by-products

7.3.1.1.1 In the food industry

At the beginning of 21st century, apple pomace was successfully introduced into baked food products as dietary fiber, because of its supremacy over cereal brans and legumes. Recently, these by-products have been utilized in the production of meat products and yogurt (Choi et al., 2016; Wang, Kristo, & LaPointe, 2019; Yadav, Malik, Pathera, Ul Islam, & Sharma, 2016). Defatted apple seeds are incorporated into chewing gum (Gunes, Palabiyik, Toker, Konar, & Kurultay, 2019), and apple pomace in addition with oat bran is used as a stabilizer for oil–water emulsions (Huc-Mathis, Journet, Fayolle, & Bose, 2019).

7.3.1.1.2 In biotechnology

Apple pomace is used as a substrate for microorganisms to generate value-added products, such as enzymes, aroma compounds, and organic acids. Such by-product substrates are cheaper than other used sources of carbon for the production of propionic and acetic acid using microbial techniques. Thus the use of apple pomace in biotechnological processes seems to be an attractive prospect. The other biotechnological utilization of apple pomace is the production of citric acid (124 g citric acid was produced from 1 kg dry apple pomace) using microbes, that is, *Aspergillus niger*). The enzymes (polygalacturonases or hydrolytic depolymerases) obtained from apple pomace are involved in the degradation of pectic substances and offer a wide range of applications.

7.3.1.1.3 In the pharmaceutical industry

The biomolecules of the polyphenolic group (phloridzin) are one of the main constituents of apple pomace and have antidiabetic and antioxidant activities, prevent bone loss, enhance memory, and inhibit cancer cells (Nair, Ziaullah, & Rupasinghe, 2014). The most bioactive phenolic compounds (flavonoids, hydroxycinnamic acids, dihydrochalcones) in apple are found in the peels and are closely associated with health-promoting properties, for example antioxidant, antiinflammatory, and antimicrobial. Hence, these bioactive compounds could have pharmaceutical applications (novel dermal formulations), and high levels of pectin in apple pomace could be used in the pharma industry as a natural gelling agent.

7.3.2 Citrus fruit by-products

Citrus fruits are the most widely consumed and produced commercial fruits in the world. They belong to the botanical family Rutaceae and subfamily Aurantioideae. The global production of citrus fruits 2019–20 was 7.8 MMT, whereas juice and tangerine/mandarin production were estimated at 1.6 million tons and 31.6 million tons, respectively (USDA, July 2020). The main by-products of citrus fruits are peels, which are 50% of the original fruit weight, along with internal tissues (30%–35%) and seeds (0%–10%). The industrial processing of peels produces essential oils and pectin. The main focus in citrus by-products is insoluble fiber, which is generally obtained during the recovery process of essential oils. Citrus peels contain numerous bioactive molecules, for example, polyphenols, essential oils, and vitamins (Mamma & Christakopoulos, 2014; K. Sharma, Mahato, Cho, & Lee, 2017). In total, almost 70% of the dry weight of citrus peels is composed of dietary fibers. The by-products of citrus fruits include an enormous source of natural flavonoids like hesperidin, naringin, and narirutin, flavonols, like rutin and quercetin, and flavones like diosmin and tangeretin (Chen & Kitts, 2017; Conidi, Cassano, & Drioli, 2012; Papoutsis et al., 2018). Some unique phytobiomolecules found in this by-product include flavanones, flavanone glycosides, and polymethoxylated flavones, along with some phenolic acids like hydroxycinnamic and hydroxybenzoic acids (Negro, Mancini, Ruggeri, & Fino, 2016; Papoutsis et al., 2018). Furthermore, peels are also a good source of essential oil with d-limonene and pectin (Marić et al., 2018). The antioxidant effect of citrus seed is greater than that in peels, in which hesperidin and eriocitrin-like biomolecules are present (Qiyang et al., 2020).

7.3.2.1 Sustainable applications of citrus by-products

7.3.2.1.1 In the food industry

Citrus fibers have the characteristics feature of heat stability, and as a result citrus fibers have effective health and functional benefits. Hence, they have been utilized in meat, dietary, and bakery industries. They also enhance bacterial growth and survival (e.g., *Lactobacillus* and *Bifidobacterium* spp.) as probiotics and are very promising in fermented milk products. Citrus by-product components like pectin are utilized in food industries in the preparation of jams, jellies, and marmalades as a thickening, emulsifying, and stabilizing agent and in edible films for active food packaging (polymeric matrix) systems (Espitia et al., 2014; Satari & Karimi, 2018). Citrus peel oils have been proven to possess antimicrobial and antifungal properties and to be comparatively safe as food additives, and are utilized as alternative and reliable flavor additives.

7.3.2.1.2 In biotechnology

Citrus by-products (peels) are utilized in the solid-state fermentation (SSF) process as a substrate for various genera of fungi (i.e., *Aspergillus*, *Fusarium*, *Neurospora*, and *Penicillium* etc.) for the successful production of bioactive fermented products like pectinolytic, cellulolytic, and xylanolytic enzymes. Moreover, they are used in the revalorization of by-products by using them in the production of biogas (anaerobic digestion), high-added value chemicals, and biofuel precursors through fermentation techniques, isolation of valuable biomolecules, and overall maintaining of the sustainable supply chain (Chavan, Singh, & Kaur, 2018; Mahato, Cho, & Lee, 2017; Putnik et al., 2017; Satari & Karimi, 2018; K. Sharma et al., 2017).

7.3.2.1.3 In the pharmaceutical industry

One of the main chemical by-products from citrus fruits is naringenin (4,5,7-trihydroxy-flavanone) which has antidiabetic effects (Den Hartogh & Tsiani, 2019) and can be utilized in the pharmaceutical industry for the management of diabetes in different dosage forms. Various phenolic compounds obtained from citrus by-products have shown favorable pharmacological properties like antioxidant, antitumor, and antiinflammatory actions (Mahato et al., 2017). The citrus biomolecule d-limonene has been used as a therapeutic agent against lung, breast, gastric, colon, and prostate cancers (Yu et al., 2019). Other than the use of citrus fruits in food industries, pectin derived from citrus fruits also has therapeutic potential. Pectin modified at high temperature has been used in cancer therapy because of its antiadhesive and apoptosis properties. Essential oils obtained from citrus by-products have been used in recently in cosmoceutical industries, home care remedies, and aromatherapy.

7.3.3 Grape by-products

Global grape production in 2019−20 was estimated at around 23.4 MMT (USDA, July 2020) and of that, about half of the global production is utilized in wine industries for the production of wine and the rest is used as fresh juice and for the production of raisin (dried grapes) (Bordiga, Travaglia, & Locatelli, 2019). Grape pomace is the main by-product produced in wine industries and constitutes about 15%−20% of the weight of the original fruit. Generally, it contains grapefruit peels, residual fruit pulp, and seeds and it is estimated at nearly 5.6−7.5 Million metric tons every year. Until the last decade, not much value was placed on the utilization of such by-products except in the preparation of some traditional distillate, animal feed, or to an extent as a fertilizer, however the valorization of this by-product has increased over the last few years (Bordiga et al., 2016). Grape pomace is comprised of dietary fibers, mainly hemicelluloses, cellulose, and pectin. Other polyphenols which are predominantly found in grape pomace are phenolic acids, flavanols, flavonols, stilbenes, anthocyanins, etc. (Mattos, Tonon, AL Furtado, & Cabral, 2017). In grape pomace, approximately 40%−50% dry weight consists of grape seeds. Grapes seeds also contain numerous types of polyphenols like gallic acid, caftaric acid, catechin, epicatechin, epicatechin gallate, procyanidins, etc., along with proteins, lipids, carbohydrates, and vitamin E. Seed oils obtained by the cold compression technique consist of biologically active compounds and hence are used as a rejuvenator.

7.3.3.1 Sustainable applications of grape by-products

7.3.3.1.1 In the food industry

Phenolic acids, flavonoids, anthocyanins, and proanthocyanidins bioactives present in by-products of grape pomaces are FDA-approved as a natural colorant in some beverages and even as food preservatives (Piemontese, 2016). A "clean level" food initiative has been taken by substitution of artificial antioxidants with natural antioxidants from grape by-product extracts with the intention of solo natural components with greater safety and shelf-life (fatty foods) at elevated temperatures. Furthermore, grape by-products are used as a functional ingredient in the meat and fish industries (Brenes, Viveros, Chamorro, & Arij, 2016; Mainente, Menin, Alberton, & Zoccatelli, 2019). Thermal processing is one of the essential steps in food-processing industries and has a deeply negative impact on bioactive molecules. Polyphenolics of grape peel enhance the bioavailability and biological potentials such as antioxidant and antimutagenic properties of end products while processing through the thermal process, making more useful and sustainable utilization compared to existing chemicals in this range (Vodnar, Călinoiu, Dulf, Ştefănescu et al., 2017; Vodnar, Călinoiu, Dulf, Eugenia et al., 2017). Grape seed oil is composed of a significant quantity of polyunsaturated fatty acid [linoleic acid (≈70%), oleic acid (≈15%), palmitic acid (≈7%), and stearic acid (≈3%)] and vitamins (tocopherols and tocotrienols), hence it is considered as a trusted ingredient for nutraceuticals or functional foods (Fiori et al., 2014). Pomace powders are characteristically gluten-free and added to muffins and brownies. They can provide additional dietary fiber and antioxidant levels, along with nearly 15% flour replacement in baked goods including yeast bread.

7.3.3.1.2 In biotechnology

Unlike citrus by-products, grape by-products also have been utilized in the fermentation process as a biotechnological conversion substrate medium for the production of various hydrolytic enzymes including xylanases, cellulases, pectinases, etc.

7.3.3.1.3 In the pharmaceutical industry

Extracts of grape by-products have been proven to possess antibacterial and antifungal activities. In addition, their inflammatory or antiaging potential (Petersen & Smith, 2016) has led them being a potent biochemical ingredient in the cosmetic industry. Resveratrol, a natural molecule found in the outer skins of red grapes, is widely used as an antioxidant and protective antiaging agent, and is used in the cosmetic industry in the manufacture of soaps. The presence of numerous bioactive chemicals in grape seed oil imparts antimicrobial, antiinflammatory, cardioprotective, and anticancer effects, which make it pharmaceutically significant (Garavaglia, Markoski, Oliveira, & Marcadent, 2016).

7.3.4 Tropical fruits by-products

7.3.4.1 Mango by-products

Mangifera indica, commonly known as mango, has been designated as the Indian national fruit. It is the most popular tropical exotic fruit in the world because of its elegant appearance, flavor, and taste. As per the available FAO (2017) data, annual global mango production is 50.65 million tons and the major producer in India with 38.5% of total production (http://www.fao.org/faostat/en/#data). The mango by-products mainly consist of peels and seeds, which contribute nearly 35%−60% of the original fruit mass (Schieber, 2017; Schulze-Kaysers, Feuereisena, & Schieber, 2015). Mango products include concentrates, syrup, pickles, chutney, puree, etc., along with the production of a huge quantity of mango by-products. Among the mango by-products, peels constitute around 7%−24%, seed 10%−25%, and kernel 20% of the whole fruit (Jahurul et al., 2015). Mango by-products are rich in bioactives, such as dietary fiber and phenolic compounds (tannins, gallates, gallic acid, and gallotannins in peels, and ellagic acid and its derivatives in seeds), alkylresorcinols, flavonoids, proanthocyanidins, carotenoids, sugar (glucose, galactose, arabinose), and vitamins (Kumar, Yadav, Muthukumar, & Garg, 2013). This has resulted in them being utilized widely in the pharmaceutical, food, and cosmetic industries. Pectin is another promising component found widely in mango peels, and it has more advantages than apple pectin as it is less susceptible to enzymatic degradation (Geerkens et al., 2015).

7.3.4.1.1 Sustainable applications of mango by-products

In the food industry Mango by-products, that is, dried peel and kernel powder, are utilized as functional food ingredients in the manufacture of biscuits and macaroni in food industries, and even the kernel oil is used as an essential food additive. Recently, mango peel extract unified with gelatin-based film was used in a food packaging material with improved antioxidant potentials and improved film strength capabilities, resulting in a low-cost coating and packaging materials for the pharma industries (Adilah, Jamilah, Noranizan, Nur, & Hanani, 2018). In addition, mango peels are used in edible films because of their higher permeability and hydrophobicity. Mango kernel extracts significantly improve the biopolymer films made with isolates of soya protein or fish gelatine in terms of their thickness, tensile strength, and antioxidant activity (Maryam Adilah, Jamilah, & Nur Hanani, 2018).

In biotechnology Mango by-products (peels) are used in fermentation industries as viable fermentation substrate for the production of lactic acid and production of enzymes such as pectinase. The kernels and seeds are also used in the industrial production of α-amylase enzymes (Jawad, Alkarkhi, Jason, Easa, & Nik Norulaini, 2013).

7.3.4.2 Banana by-products

The banana fruit belongs to the *Musa* genus, one of the most ancient, traditional, and highly cultivated fruit crops in the world. It has a great impact on tropical areas in terms of foodstuffs and the bio-economy. Global banana production was estimated at around 115.74 MMT in 2019 (Shahbandeh, 2020; http://www.statista.com). India has the largest share of world banana production, and about 90% is domestically consumed as fresh fruit. In the industrial processing of banana nearly 5% was utilized, with purely processed banana products constituting nearly

2.5% and the remainder utilized as an additive in other foods. Despite their consumption as fruit, all producers of bananas generate tons of underused by-products and wastes. Banana fruit production leads to the production of massive amounts of by-products such as peels, rhizomes, fruit stalks, inflorescences, leaves, and pseudo-stems. These wastes have hidden potential as a renewable resource for green technology, food matrices, and pharmaceutical agents, due to the presence of valuable bioactive molecules (Mathew & Negi, 2017; Pappu et al., 2015; Vu, Scarlett, & Vuong, 2018). Various levels of phenolic acids, hydroxycinnamic acid, vitamins, flavonoids, carotenoids, carbohydrates, carbohydrate-binding proteins, enzymes, alkaloids, saponins, terpenes, anthraquinones, cardiac glycosides, fatty acids, sterols, triterpenoids, etc are found in banana ripe pulps, depending on their level of ripening (Mathew & Negi, 2017). Plantain flower, rhizomes, fruit stalks, inflorescences, leaves, and pseudo-stems are rich in secondary metabolites including glycosides, tannins, saponins, phenols, steroids, and flavonoids (Padam, Tin, Chye, & Abdullah, 2014). The most common by-product of banana is banana peels (nearly 35% of the total original fruit), which contains a significant amount of bioactive molecules such as phenolics like hydroxycinnamic acids, flavonoids, phytosterols, carotenoids like lutein, β-carotene, α-carotene, violaxanthin, auroxanthin, neoxanthin, isolutein, β-cryptoxanthin and α-cryptoxanthin, anthocyanins, biogenic amines, various vitamins like vitamin B3, B6, B12, C, and E, dietary fibers like cellulose, lignin, resistant starch, pectin, and hemicelluloses with potent antioxidant activity (Amini Khoozani, Birch, & Ahmed Bekhit, 2019; Garcia-Amezquita, Heredia-Olea, & Welti-Chanes, 2018; Müller, Caris-Veyrat, Lowe, & Böhm, 2016; Müller-Maatsch, Bencivenni et al., 2016; Vu et al., 2018). The pectin content and composition vary from different food waste streams. Furthermore, biomolecules like gallocatechins are found in five times greater quantities in peels than fruit pulp.

7.3.4.2.1 Sustainable applications of banana by-products

In the food industry Tender banana stem is generally used as a vegetable and has high medicinal value. Sweet candy is prepared from tender banana pseudostem, and banana stem waste is a very good source of cellulose. Banana peels and flours (obtained at various stages of ripening) are utilized as a source of nutritional constituents and food additives for value-added food materials (Radoi, Isidora Radulov, Morvay, Stroe Mihai, & Trasca, 2015; Segundo, Román, Lobo, Martinez, & Gómez, 2017). Unripe banana peel flour is beneficial for colon health because of the crystalline structure of resistant starch. On the other hand, ripened peel flour has better digestibility due to a high amount of starch and proteins (Amini Khoozani et al., 2019). Banana peel flour is advantageous over normal wheat flour as it decreases the glycemic index and hydrolysis index when integrated with bread and also because it remains intact after thermal or mechanical processing.

In biotechnology In the field of fermentation technology, carbohydrate-rich banana by-products like peels are used as a substrate in the biotechnological conversion process for SSF, which is closely associated with the production of various enzymes (laccase) and organic acids (citric, lactic, and acetic) using various microorganism strains (*Trametes pubescens*, *A. niger*, *Yarrowia lipolytica*, etc.) (Bharathiraja S et al., 2017; Panda, Mishra, Kayitesi, & Ray, 2016).

Bioethanol One of the recent sources of transportation fuel worldwide is bioethanol derived from fermentation. Bioethanol is also obtained from a variety of raw materials like corn starch, sugar cane, and lignocelluloses contained in waste materials. Ethanol produced from banana peels by fermentation provides greater practical feasibility due to its low cost compared with other sources. The indigenous yeast (*S. cerevisiae*) with good fermentation attributes enhanced ethanol yield and minimized the cost of production obtained from ripe banana peels. Proteins and fats of banana peel by-product serve as essential nutrients for yeast growth, in addition to playing a vital role in the structural and biological functions of the cell (Table 7.1).

In the pharmaceutical industry The bioactive molecules present in banana by-products such as peels have antimicrobial, antihyperglycemic, antioxidant, antiinflammatory, and antiaging properties. They also have a major role in lowering plasma lipid oxidation and lipoproteins along with decreasing cholesterol levels (Kapadia, Pudakalkatti, & Shivanaikar, 2015; Vu et al., 2018). The presence of vitamin A in bananas and plantains helps in digestion, whereas boiled and mashed ripe fruit can be used to treat constipation. The juice from the male bud provides an apparent remedy for stomach problems in people of all ages. The pounded peels of ripe bananas can be used to make a poultice for wounds and the inside peel has antiseptic properties when wrapped directly around wounds or cuts in an emergency. Weaning food based on plantain is nutritious for babies and can be used to overcome malnutrition and kwashiorkor resulting from protein deficiency.

In agriculture Banana peels and other by-products are readily used as a fertilizer for the growth of different types

TABLE 7.1 Topical fruits and their sustainable utilization.

Fruit	By-products	Major bioactives principles	Food industry	Pharmaceutical industry	Biotechnology	References
Apple	Defatted apple seeds, apple pomace	Phloridzin, pectins, cellulose, hemicelluloses, lignins	Chewing gum, stabilizers for oil–water emulsions	Antidiabetic, antioxidant	Substrate for microbial fermentation	Gunes et al. (2019), Huc-Mathis et al. (2019), Nair and Rupasinghe, (2014)
Citrus	Citrus peels, citrus peel oils	Hesperidin, naringin, narirutin, rutin, quercetin, diosmin, tangeretin	Probiotics, food additives, flavor additives	Antidiabetic, antioxidant, antitumor, antiinflammatory	Solid-state fermentation process as substrate	Chen and Kitts (2017), Papoutsis et al. (2018), Mahato et al. (2017)
Grape	Grape pomace, grape seeds	Hemicelluloses, cellulose, pectin, polyphenols, phenolic acids, flavanols, flavonols, stilbenes, anthocyanins	Nutraceuticals, functional foods, muffins, brownies	Antioxidant, protective antiaging agent, antimicrobial, antiinflammatory, cardioprotective, anticancer	Fermentation substrate for microbial growth	Mattos et al. (2017), Garavaglia et al. (2016)
Mango	Mango peels, mango seeds	Dietary fiber, phenolics, alkylresorcinols, flavonoids, proanthocyanidins, carotenoid, sugar	Functional food, food packaging material, food additives	Coating and pharmaceutical packaging materials	Industrial production of α-amylase enzymes	Jawad et al. (2013), Adilah et al. (2018), Lee, Lee, Yang, and Song (2015).
Banana	Banana peels, plantain flower, rhizomes, fruit stalks, inflorescences, leaves, and pseudo-stems	Phenolics, flavonoids, phytosterols, carotenoids, α- cryptoxanthin, anthocyanins, biogenic amines	Sweet candy, nutrient and food additives	Bioethanol, antimicrobial, antihyperglycemic, antioxidant, antiinflammatory, antiaging	Substrate in biotechnological conversion process for solid-state fermentation	Bharathiraja et al. (2017) Panda et al. (2016), Segundo et al. (2017), Radoi et al. (2015)
Avocado	Avocado peels and seed	Phenolics, carotenoids, vitamins	Cream soup, food packaging, colorants in food products	Anticancer, antidiabetic, antihypertensive	Biodiesel production	Chel-Guerrero, Barbosa-Martín, Martínez-Antonio, González-Mondragón, and Betancur-Ancona (2016), Araújo et al. (2018), Palma, Lloret, Puen, Tobar, and Contreras (2016)

of plants. It is available as agricultural waste, and is utilized as a potential growth medium for a local yeast strain which acts as a biofertilizer. The rich carbohydrate content and other basic nutrients support yeast growth to maintain agricultural crops. Banana peels act as a good stimulating soil conditioner through the SSF process. Composted banana peels can be converted into organic fertilizer. The bacterium species like *Azospirillum*, *Azotobacter*, and phosphate-solubilizer found in banana peels enhance soil properties.

Miscellaneous The large leaves of bananas have diverse uses as a "biological plate" for serving food in southern India, where bananas are cultivated exclusively for their leaves. They can be used for making cigarette papers and hats and also provide packing material, and the leaf sheaths can be used as water runways. Furthermore, banana seeds are used for making necklaces and other ornaments, as well as the sap of the banana as a dye, the fruit as a meat tenderizer, and banana ash in soap. In Indonesia, floor wax and shoe polish are manufactured from banana peels. Banana fiber extracted from banana tree bark is used for making various products with attractive designs of coasters, table mats, bags, and runners. Banana board is a potential substitute for wood products like plywood and medium-density boards.

7.3.4.3 Avocado by-products

Persea americana Mill belongs to the family Lauraceae, commonly known as avocado, and is an evergreen tree cultivated in tropical regions and mostly cherished for its nutritious fruits. The estimated total global production for avocados in 2018 was around 6.40 MMT (FAO, 2018). Avocado has high nutritional value due to the presence of different amino acids, fibers, and unsaturated fatty acids. It is also enriched with bioactive substances such as soluble phenolics, carotenoids, vitamins (C, D, E, B6, B12), and minerals. Industrial processing of avocado fruit generates significant agro-industrial by-products which include mainly peel and seed (18%–23% based on the dry weight). They are a potential source of bioactive contents such as hydroxybenzoic acid and hydroxycinnamic acids, procyanidins, flavonols, etc. (Figueroa, Borrás-Linares, Lozano-Sánchez, & Segura-Carretero, 2018a, 2018b). The presence of such biomolecules in the by-product make it a potent antioxidant and antiinflammatory agent (Figueroa et al., 2018a, 2018b). The phenolic contents (hydroxybenzoic acid and hydroxycinnamic acids) were found to be three times higher in peels compared with other parts such as the seeds and pulps, making peels a potent antioxidant (Melgar et al., 2018). Despite the high bioactivity of the peels due to the presence of phytochemicals, instability of biomolecules (phenolics) upon exposure to light, temperature, metallic ions, oxidative, enzymatic conditions, and altered pH have made their usage limited. The transformation of avocado by-products into value-added components using green methods includes biosolvent (ethanol), accelerated solvent, or ultrasound-assisted extraction (UAE), etc.

7.3.4.3.1 Sustainable applications of avocado by-products

In the food industry The potential use of avocado by-products (dried peels) is in the formulation of functional beverage formulations because of the high antioxidant profile (Rotta et al., 2016). The seed starch (modified cross-linking) significantly improves the structural properties of cream soup (Cornelia & Christianti, 2017) and its biodegradable polymers play a great role in the food packaging area of food industries (Chel-Guerrero et al., 2016). Avocado by-products have also been used as colorants, flavorings, and thickening agents in various foods and beverages. Hass avocado (a species of largely cultivated avocado) seeds contain orange pigments which can replace the artificial colorants in food products. The peel extracts of avocado have been used in meat products for the prevention of oxidation of meat proteins. Avocado seeds are deployed as a good source of dietary fiber for daily needs and also act as functional food content for their fiber contents such as lignin, cellulose, and hemicellulose (Barbosa-Martín, Chel-Guerrero, González-Mondragón, & Betancur-Ancona, 2016).

In biotechnology The production of bioenergy from avocado by-products such as peels, seeds, pulp, etc. is a major significant contribution, along with the production of biodiesel. For example, pulp oil and seed oil are used for biodiesel production. In addition to their role as biodiesel, they also have been utilized for the production of charcoal, fuel additives, and an as a favorable adsorption metrics in the decontamination of water (wastewater treatment) (Palma et al., 2016).

In the pharmaceutical industry Avocado peel extracts serve as a potent antiinflammatory agent by inhibiting the inflammatory mediators like nitric oxide or cytokines (proinflammatory mediators) with potential antioxidant activity (Tremocoldi et al., 2018). Avocado peels and seed extracts possess potent antimicrobial action, and when the peel extract was combined with nisin (a naturally found polycyclic antimicrobial dipeptide), it showed significant antimicrobial activity against Gram-positive bacteria but little effect among Gram-negative bacteria like *Escherichia coli* (Calderon-Oliver et al., 2016). This may be due to the presence of polyphenols and tannins that are responsible for the anticancer, antidiabetic, and antihypertensive effects (Araújo et al., 2018).

7.3.5 Vegetable by-products

As with fruit by-products, various vegetables also contribute a large amount of by-products, which in most cases are either ignored or not widely known or practiced. This may be due to the infrastructural deficiency and insufficient knowledge about the valorization of such by-products in various area.

7.3.5.1 Carrot by-products

The carrot, *Daucus carota*, belongs to the family of Apiaceae and is most popular root vegetables and utilized worldwide either in raw, cooked, or juice form. Biochemically, carrots are enriched with high amounts of anthocyanidin, carotenoid, and dietary fiber, which possess biological roles such as anticancer, antioxidant, and preventive actions against cardio and digestive disease development (Clementz et al., 2019a, 2019b). Total production of carrot and turnip together was estimated at around 40 billion tons in 2018 and the main producer was China (http://www.fao.org/faostat/en/#data/QC).

Carrot by-products mainly come from industrial processing and contain mostly peels and pomace. The production of pomace is due to the low yield of carrot juice, which reaches a maximum of 30%–50% of raw materials. It contains valuable biomolecules such as carotenoids, dietary fiber, uronic acids, and neutral sugars (Vodnar, Călinoiu, Dulf, Ştefănescu et al., 2017; Vodnar, Călinoiu, Dulf, Eugenia et al., 2017). Pectin is an important constituent of carrot peel, composed of D-galacturonic acid, L-rhamnose, L-arabinose, and D-galactose. This dietary fiber is mainly utilized as a food additive in functional food products such as low-calorie foods, frozen foods, jams, and jellies. The presence of potent antioxidant capacity and prebiotic features due to fiber (Liu, Jin, Feng, Yang, & Fu, 2019) renders them as an alternative to nutraceuticals. The virtue of pectin density and gel make this a suitable replacement for hydrocolloids (Encalada et al., 2019). In addition, peels also serve as an ideal source of carotenoids, especially α- and β-carotene. Carrot pomace is also used in bioethanol production (Clementz et al., 2019a, 2019b).

7.3.5.1.1 Substantial applications of carrot by-products

In the food industry The fibers derived from carrot by-products are utilized in the production of fiber-enriched cookies and also as a probiotics source for gut microflora. The essential oils of carrot by-products are utilized in the flavor industry and as a preservative in the food industry due to its potent antimicrobial action (Chiboub et al., 2019). It is also utilized in the production of biodegradable and edible plastics thanks to its nutritional and sensory properties (Otoni et al., 2018). Furthermore, the acceptable mechanical and biodegradability properties of carrot by-products ensure it as an effective and essential material in the food packaging area.

In the pharmaceutical industry Carrot by-products have an important biological impact on human body that has been recognized by the biopharmaceutical industry as it improves clinical conditions such as blood pressure, heart diseases, atherosclerosis, infections, bronchial asthma, and muscular degeneration. The peels contain polyphenols with antimutagenic and antitumor actions due to its free radical scavenging potential. By-products containing dietary fiber have been shown to have a preventive action against heart diseases, high blood sugar, cancer, and constipation. Various enzymes derived from carrot by-products such as glucocerebrosidase, α-galactosidase-A, and deoxyribonuclease-I are used in the treatment of Gaucher disease, Fabry disease, and cystic fibrosis, respectively. It is the most comprehensive source of vitamin A and its metabolic product, retinoic acid, possesses well-known roles in lung function, reproduction, fetal development, and immunity-boosting (Hufnagl & Jensen-Jarolim, 2019).

In biotechnology Carrot tissues are widely used in the production of different edible vaccine. In this context, various practical prototypes have been established.

7.3.5.2 Cauliflower by-products

Cauliflower and broccoli come are Brassica crops and, among vegetables, cauliflowers have the most by-products, consisting of leaves and stem with a high waste index after harvesting, that is, the ratio of nonedible to edible portions. It has a global production of about 26 million tons annually, harvested from 1.4 million hectares of land as per data available in 2017 (http://www.fao.org/faostat/en/#data). China (40.2%; 10.4 M tons) and India (32.9%; 8.6 M tons) are the main producers of cauliflower worldwide. The main bioactive molecules of cauliflower by-products are dietary fiber, phenolic compounds (flavonoids such as kaempferol and quercetin and hydroxycinnamic acids such as caffeic, ferulic, and sinapic acids), and vitamin C. Cauliflower seeds also contains diffrent biomolecules like sinigrin, glucoiberin, and glucobrassicin etc. The major phytoconstituent repoted in this seeds are glucosinolates.

7.3.5.2.1 Sustainable applications of cauliflower by-products

In the food industry Cauliflower by-products, especially dietary fiber, are utilized in ready-to-eat foods like snacks, soups, meat products, biscuits, and juices (Amofa-Diatuo, Anang, Barba, & Tiwari, 2017; Ribeiro, Abreu, Freitas, Pumar, & Teodoro, 2015). In addition, by-products are mixed with ready-to-eat foods that are preserved for a long time due to its proven antimicrobial properties against microbial contaminations (*Listeria monocytogenes*) (Sanz-Puig, Pina-Pérez, Criado, Rodrigo, & Martínez-López, 2015a). The bioactive peptides from cauliflower by-products also have had a remarkable application as nutraceuticals recently (Montone et al., 2018; Xu et al., 2017; Table 7.2).

In biotechnology The by-products of cauliflower are utilized in the production of enzymes, that is, glucoamylase (starch and 1,4-linked oligosaccharide hydrolysable enzyme) by fermentation technology using a microorganism (*A. niger*). Supplementations of cauliflower by-products in whey induce a high yield of β-galactosidase in a short time. Also, fermentable sugar from cauliflower by-products showed remarkable practical utility (Majumdar, Naha, Bhattacharyya, & Bhowal, 2019).

In the pharmaceutical industry The biomolecules found in cauliflower by-products possess tremendous biological action against hypertension and hyperglycemia (Xu et al., 2017). The bioactive peptides found in the by-products show the promising effect of improvement in the viability of vascular endothelial cells (Caliceti et al., 2019). The seed bioactive molecule sinigrin was recently exploited for its numerous biological activities such as anticancer, antiinflammatory, antibacterial, antifungal, antioxidant, and wound-healing activities (Mazumder, Dwivedi, & Du Plessis, 2016).

7.3.5.3 Tomato by-products

Tomato (*Lycopersicon esculentum* Mill.) is the second most cultivated and consumed vegetable around the world. It is a huge source of bioactive molecules such as carotenoids [lycopene (80%−90%), β-carotene], vitamin C, vitamin E, and various phenolic compounds. The tomato wastage rate is considerably high due to its high production, consumption, and industrial processing. The industrial tomato by-products contain significant amounts of bioactives with antioxidant property. The major by-products of tomato include peels and seeds, which are around 4% of the total original weight, along with tomato pomace which contains a significant amount of insoluble fiber along with glucose, fructose, and protein (Azabou et al., 2016).

7.3.5.3.1 Sustainable applications of tomato by-products

In the food industry Whole tomato by-products are mainly utilized for animal feeds and contain sugars (19.27%), protein (7.55%), pectin (5.85%), fat (3.92%), and minerals. Tomato fiber is the main component of tomato by-products, along with oils of tomato that have high nutritional and economical values as antioxidants and that are used in human nutrition as a functional food in the food industry.

TABLE 7.2 Vegetable by-products and their use.

Vegetable	By-product	Major bioactive principles	Food industry	Pharmaceutical industry	Biotechnology	References
Carrot	Carrot peels, carrot pomace	Anthocyanidin, carotenoid, dietary fiber	Biodegradable and edible plastics	Anticancer, antioxidant, preventive action for cardio and digestive diseases	Edible vaccine	Clementz et al. (2019a, 2019b), Chiboub et al. (2019)
Cauliflower	Leaves, stem, and seeds	Sinigrin, dietary fiber, phenolic compounds, vitamin C	Ready-to-eat foods, nutraceuticals	Hypertension, hyperglycemia	Production of enzymes, i.e., glucoamylase	Sanz-Puig et al. (2015a), Xu et al. (2017), Caliceti, Urao, Rizzo, and Giuliano (2019), R. Sharma, Oberoi, and Dhillon (2016).
Tomato	Peels, seeds, pomace	Carotenoids, vitamin C, vitamin E, phenolic compounds	Functional food	Antioxidant, carcinogen-protectives		Müller, Caris-Veyrat et al. (2016), Müller-Maatsch, Bencivenni et al. (2016)

In the pharmaceutical industry The tomato by-product biomolecules are gaining significant importance for their antioxidant and carcinogen-protective properties in the pharmaceutical field. Biomolecules obtained from tomato by-products have cardiovascular diseases preventive qualities (Müller, Caris-Veyrat et al., 2016; Müller-Maatsch, Bencivenni et al., 2016).

7.3.5.4 Miscellaneous vegetable waste and by-products

There are many vegetables that have a tremendous impact in this area, one of which is cardoon (*Cynara cerdunculus*), which synthesizes and accumulates inulin, a polysaccharide belonging to the family of fructans. Inulin has an extensive range of therapeutic uses such as a vehicle in a drug-delivery system, and a dietary fiber with additional health benefits. Inulin has experienced increased demand in the biotechnology industry as a potential source of fructose. Inulin is mainly extracted from chicory, Jerusalem artichoke, stevia, onion, and garllic. The chemical structure of inulin is based on linkage of fructose units, that is, β-(1$\longrightarrow$2) ending with an α-(1$\longrightarrow$2) glucose. The nonedible by-products of cardoon or artichoke consist of valuable minerals and phytobioactives, where the green parts contain polyunsaturated fatty acid (α-linolenic acid and tocopherols) and phenolic acids (Chiboub et al., 2019). Some more bioactive chemicals like saponins, flavonoids (rutin, quercetin glycoside, isoquercetin), hydroxycinnamates, and phenolic acids (chlorogenic acid, *p*-coumaric, caffeic, and ferulic acids) are found in high quantities in asparagus (*Asparagus officinalis*) which is also well known for its enrichment with dietary fiber. As already mentioned, a primitive bioactive in asparagus is saponins, which are a group of compounds consisting of steroidal aglycones linked with oligosaccharides making them highly amphipathic, acting as a foamer and emulsifier (Hamdi et al., 2018) that are commercially utilized in the food (cellulose nanocrystals), cosmetic, and pharmaceutical industries. Therapeutically, saponins are found to have various potent actions such as antiinflammatory, antimicrobial, anticarcinogenic, cytotoxic, and antioxidant properties (Sparg et al., 2004). Asparagus waste contains the most important saponins, identified as protodioscin and dioscin. Asparagus powders obtained from by-products showed high amounts of total dietary fiber (62%−77%) and were chemically comprised of cellulose, klason lignin, soluble sugars, protein, cellulose. etc. Nanocellulosic materials obtained from asparagus are a new environmentally friendly emulsifier for the food processing industry that have attracted great interest recently. Similarly, the vegetable by-products, seed extracts of cucumber (*Cucumis sativus*), pumpkin (*Cucurbita pepo*), bitter gourd (*Momordica charantia*), bottle gourd (*Lagenaria siceraria*), and tinda (*Praecitrullus fistulosus*) have higher phenolic compound contents, which exhibited high effectiveness against pathogenic microbes, such as *E. coli*, *Fusarium oxysporium*, *Streptococcus thermophilus*, *Serratia marcescens*, and *Trichoderma reesei* (Sonia et al., 2016; Sood et al., 2012).

Vegetables by-products and their uses have been summarized in Table 7.2.

7.4 Innovative drying techniques and extraction methods for fruit and vegetable by-products

Fruit and vegetable processed by-products contain high-value food components (bioactives). The recovery of these sensitive components and their drying process has to be highly operative and economical for imperative to develop low-cost high-value food ingredients. The important step for the sustainable use of plant by-products as food is drying. After drying, by-products are converted into high-value ingredients as a powdered form which can be used for industrial purposes. Drying not only reduces the volume compared to raw materials but also increases the shelf-life and transportability by lowering the water content. Drying is an energy-intensive process and has a great impact on biomolecules and their biological activities. For example, improper drying or energy fluctuations can reduce the phenolic and pigment contents in fruit and vegetables. Moreover, it can alter the biological activities also (such as antioxidant potentials) in the biological system. Therefore a proper method of drying is required for sustainable utilization of by-products. Some of these approaches are discussed below.

7.4.1 Infrared-assisted convective drying

Infrared-assisted convective drying is a potential and promising industrial method that works by absorbing the infrared radiation which supplies energy to the sample causing rapid heating without requiring a transfer medium (Łechtańska, Szadzińska, & Kowalski, 2015). This method also improves the properties of dried products in terms of quality, that is, retention of color, liquid-holding capacity, total biomolecules (phenolics), etc. in raw by-products (orange peels and leaves). Moreover, infrared can be easily combined with other conventional drying methods. For example, combined infrared and convective drying can cause less harm to the phenolic compounds in grape pomace as compared to individual methods, for example, infrared or convective drying.

7.4.2 Microwave and combined microwave drying

Microwave combined with convective drying remarkably reduces unwanted oxidation in biomaterials along with the drying time. Microwaving generally produces heat via molecular fraction, thus the heat is generated deep within the product to be dried (Parit et al., 2017). Despite a shorter time, this combined method has certain drawbacks, for example, irregular heating, probable textural damage, and inadequate penetration. To retain the advantage of short time and to overcome the drawbacks, a suitable combination with other drying methods such as microwave-assisted freeze-drying (MFD) has been adopted.

7.4.2.1 Microwave-assisted freeze-drying

This method has the potential to produce high-quality dried products at low cost as compared with the freeze-drying technique alone. This is one of the best methods for restructured products with uncompromised quality. However, MFD is not very suitable for food materials with higher moisture contents due to the low dielectric constant. Vacuum microwave drying, microwave-assisted spouted bed drying, and pulse-spouted vacuum-microwave drying are other innovative techniques which can be considered as case-specific. In addition, some other techniques like ultrasound (US), pulsed electric field (PEF), high hydrostatic pressures, etc. also can be used to counter the heat damage to thermolabile foods stuffs. Freeze-drying coupled with a microwave heat source speeds up the drying rate and yields good-quality products provided the operating unit is designed and operated to ensure the absence of hotspot developments (Fan et al., 2019).

7.4.3 Green technology: by-product extraction techniques

Extraction of fruit and vegetable by-products is the main key to its cost-effective sustainable utilization in society (Siles, Vargas, Gutiérrez, Chica, & Martín, 2016). Biomolecules extraction can be done by conventional or nonconventional technologies which have their own merits and demerits. Currently, nonconventional technology or green technology is gaining popularity in the area of by-product extraction because of its high quality, short processing time, high yield, and overall minimal waste generation. Hence green technology is slowly replacing conventional extraction techniques. Green extraction technology is a technique based on newer experimental design and discovery. These techniques of extraction ensure safe and high-quality extract/product with reduced energy consumption for alternative solvents and renewable natural products. Various green technology extraction techniques have been explored to obtain biomolecules from by-products. *Enzyme-assisted extraction* is a novel and efficient alternative technique to existing conventional methods for the extraction of cytoplasmic scattered phytochemicals and also the phytomolecules possess a hydrogen or hydrophobic bond in the network of polysaccharide lignins, which is difficult to extract with conventional methods. The extraction of biomolecules like carotenoids, anthocyanins, etc. from vegetable and fruit by-products has been successfully explored using this technique (Ghosh & Biswas, 2015; Lotfi, Kalbasi-Ashtari, Hamedi, & Ghorbani, 2015). Furthermore, the yield and recovery of biomolecules such as phenolics extracted from by-products have been increased successfully using enzymes like pectinase, Celluclast, and protease, (Stambuk et al., 2016). *Pressurized liquid extraction* or accelerated solvent extraction is an efficient method of extraction as a wide number of bioactive molecules with a variety of biological activities. The salient features of this technique include lower solvent consumption, higher extraction yield, shorter time, and reproducibility. However, reusability of solvent also facilitates the extraction of other samples by elevating to a certain pressure (100−140 atm) and temperature (50°C−200°C), which promotes better dissolution and desorption of bioactives in plant materials (Mandal & Das, 2015). The endothermic and spontaneous process in the green extraction method is known as microwave-assisted extraction (MAE). It benefits from simplicity, higher productivity, less solvent, shorter extraction time, and low processing and set-up costs (Moreira et al. 2017; H. F. Zhang, Yang, & Wang, 2011). This technique involves wave transmission from electromagnetic radiations within the frequency range of 300 MHz to 300 GHz but the most commonly used frequency is 2450 MHz (~600−700 W energy). The radiated energy or microwaves absorbed by the medium which are converted into thermal energy facilitate the process of extraction by disruption of the hydrogen bond in the cell structure. Various biomolecules like flavonoids (hesperidin), phenolic compounds (gallic acid), phenolic biomolecules like gallic acid obtained from chokeberries, flavonoids from *Terminalia bellerica*, and phenolic compounds from apple pomace were found to be the highest using MAE as compared with conventional extraction methods (Chandrasekar, San Martín-González, Hirst, & Ballard, 2015; Krishnan & Rajan, 2016; Simić et al., 2016). A simple and low-cost extraction technique that makes use of US ranging between 20−2000 kHz causing the expansion and compression of the cell-matrix inducing cell wall permeability for better yield is known as UAE. Basically, this technique act in two ways, one is enhanced solvent diffusion into the cell and the other is rinsing the cell contents after cell disruption. Intensification of mass transfer, particle breakdown, and increased solvent accessibility, etc. are the possible mechanisms behind this technique with some vital operational factors, for example, temperature, frequency, pressure, and time (Shen & Guo, 2017). This method is popular in the extraction of liquid–liquid or liquid–solid samples. An US elevated frequency of >20 kHz potentially influences the physicochemical properties of phytoconstituents with the generation of free radicals (Safdar et al., 2016; Shen & Guo, 2017). Phyto-principles such as tannins, phenolic acids (caffeic acid, ferulic acid, *p*-coumaric acid, etc.), and polysaccharides are generally extracted by this method although, in food industries, UAE is employed for sterilization and preservation purposes also (L. Zhang, Zhao, Lai, Chen, & Yang, 2018). Another well known method is PEF-assisted extraction which makes use of electricity for extraction for generating heat. Usually, high-voltage electrical pulses are passed to the materials through the electrode for the shortest duration (microseconds to milliseconds) of time that results in devastation of the cell structure and the biomolecules are separated in the cell suspension as per their ionic charges. The tissue cytomembrane disintegration caused by this technique leads to higher yields due to a change of cell permeability and increased mass transfer in the cell. This technique has been successfully applied for the extraction of phenolic compounds and anthocyanins from fruit and vegetable by-products such as grape peels, which showed improve color, content stability of

TABLE 7.3 Advances in by-product extractions techniques.

Extraction technique	Bioactive compounds	Source	Solvent/ enzyme	Yield	References
Enzyme-assisted extraction	Carotenoids Anthocyanins Carotenoid	Pumpkin *Crocus sativus Capsicum annuum*	Pectinex UltraSP Pectinex Viscozyme L, cellulase and pectinase	2 mg/100 g 6.7 mg/g 41.72–279.83 mg/100 g	Ghosh and Biswas (2015), Lotfi et al. (2015), Nath, Kaur, Rudra, and Varghese (2016)
Ultrasound-assisted extraction	Carotenoids (all-*trans*-lycopene, β-carotene) Total phenolic Naringin (flavonoid) Phenols, antioxidant, anthocyanins Natural color	Tomato pomace Red grape pomace Grapefruit solid waste Grape seeds Pomegranate rinds	Hexane and ethanol Water Ethanol Ethanol Water	7.49–14.08 mg/100 g dry weight 50,959 ppm GAE in dry extract 24–36 mg/g dw 5.41 mg GAE/100 mL 2.29 mg/mL 20%	Drosou, Kyriakopoulou, Bimpilas, Tsimogiannis, and Krokida (2015), Garcia-Castello et al. (2015)
Pulsed electric field extraction	Anthocyanin Phenolics and anthocyanin content Polyphenols Phenolic Phenolic content Carotenoids	Grape by-products Blueberry press cake Grape seeds Red grape pomace *Citrus sinensis* peels *Momordica cochinchinensis* peels	Water and ethanol 50% Ethanol and 0.5 HCl Ethanol Water Acetone in water (20%–80%) Ethyl acetate	14.05 mg Cy-3-glu eq./g dry matter Increased yield by 63% and 78% compared to conventional method 9 g/100 g GAE 52,645 ppm GAE in dry extract 12.09 mg GAE/g DW 262.3 ± 3.5 mg/100 g DW	Bobinaitė et al. (2015)
Supercritical fluid extraction	Phenolics Polyphenol content	Orange pomace (dry) Grape Seed fraction Skin fraction (grape pomace)	Pure ethanol Ethanol/water (9:1)	21.2 GAE/g of extract 20.7 GAE/g of extract 7.7 mg GAE/g 11.9 mg GAE/g	Espinosa-Pardo, Nakajima, Macedo, Macedo, and Martínez (2017), Manna, Bugnone, and Banchero (2015), Thongnuanchanand Benjakul (2014).

bioactive molecules during vinification, and also improved extraction time. This eco-friendly extraction technique can also be used in large-scale extraction of high-value bioactive molecules without significant loss of their properties (Liu, Zeng, & Ngadi, 2018) and extraction yield, chemicals, and retention of sensory quality, etc. (Puértolas and de Marañón, 2015). Supercritical fluid extraction is done with a solvent which is always above the critical point. The diffusion and surface tension of gas together provide a higher yield in the shortest possible time (Ameer, Shahbaz, & Kwon, 2017). In the food industrial sector, the most preferred solvent is carbon dioxide due to its safety and easy attainability of the critical point, that is, 30.9°C temperature and 73.8 bars pressure. Low solvent infusibility, prolongation of extraction time, high-pressure requirement, consistency, and reproducibility variation and, overall, expensive infrastructure are the other limitations of this extraction technique that obstruct its scalability (Agostini et al., 2012; Ameer et al., 2017).

These advanced methods are summarized along with their bioactive, source, solvent, and yield in Table 7.3.

7.5 Innovations and sustainable food ingredients

New or alternative foods are always in high demand. Many examples are found in the food world. By using by-products from fruits and vegetables alternative sources for healthy food development can be found and use made of secondary food products. Agro-industrial by-products may be used for functional food development but most are used in flours. For example, a pineapple core, soybean extract, and broken rice combination produced a cereal bar that was enriched with high protein, fiber, minerals, and moreover a lower caloric content. Pineapple and cactus pear peel flour has been utilized for sausages and have a great impact on the physicochemical properties (increased hydration and decreased oxidative rancidity) when cooked (Díaz-Vela, Totosaus, & Pérez-Chabela, 2015). Modern popular food products like pasta, bread, cakes, cookies, cheese, yogurt, ice cream, extruded foods, etc. are having mango peel flour, mango rinds, etc. added with good results (Serna-Cock et al., 2016). A new cereal bar was created with a combination of jabuticaba (*Myrciaria cauliflora*) with okara (*Abelmoschus esculentus*) peels flour with high-value proteins and sensorial characteristic properties (Appelt, Cunha, da, Guerra, Kalinke, & Lima, 2015). Even gluten-free cookies have been made with king palm flour with additional high dietary fiber contents and minerals such as calcium, magnesium, and potassium. The by-products of Rambutan seed fat is a potential source of cocoa butter, which is successfully substituted in confectionary industries, and even its use as a biocoagulant in the water purification or wastewater treatment industry has been well recognized. The utilization of mango seeds as processed flour is a potential ingredient for bread making, whereas Jackfruit seed flour was used as a gum in the production of low-calorie bakery products. Papaya seeds oil is well utilized in UAE (Samaram et al., 2015), extrusion expelling processes, and solvent and aqueous enzymatic extractions. Like papaya oil, papaya seed flour also has excellent foaming and emulsifying properties, and it is highly recommended for the development of functional food products. Pineapple peels are mostly utilized in bromelain production, however the pomaces of this fruit have been utilized as flour for the production of nutritional value-added extradite snacks. Also, avocado oil mostly has been added with phenolic compounds (Santana et al., 2019), sea buckthorn berry pomace also is a constituent of frozen yogurt (Terpou et al., 2019), citrus fibers are added to bologna sausage (Powell et al., 2019), berry extracts have been added to meat products (Cecchi et al., 2019), and fruit pomace, that is, grape, apple, and blueberry contains corn starch extrudates (Wang et al., 2019), Ander berry can be added to oil-in-water emulsions (Ospina et al., 2019) and berry fruit pomace can be added to Dijon-style mustard (Davis et al., 2018). Despite successful by-product utilization, the most conventional fruits and vegetable by-products are been ignored for use and development of new food products, natural extracts, and pharmaceutical products (Rtibi et al., 2018; John et al., 2019), which might be due to the pesticide residues present in the peels (Gong et al., 2019).

The extraction of various valuable bioactive constituents from by-products creates a new opportunity for the food industry. Some can provide better nutritional value with higher antioxidant, proteins, fiber, and minerals levels (De Oliveira Sancho et al., 2015; Ravindran & Jaiswal, 2016). Several bioactive compounds from these by-products have better metabolizing characteristics in humans and are properly utilized in public health for the development of numerous novel valuable products in food industries.

7.6 Strategic road map for sustainable utilization of by-products

Knowledge is incomplete unless it is being utilized. At present, insufficient information is available regarding the utilization strategy for fruit and vegetable by-products despite their extensive studies and scientific evidential reports that are publically available. Thus, their utilization in various fields, for example, aquaculture, livestock, dairy industries, and pharmaceutical industries is rarely reported and needs to be explored properly. Information

FIGURE 7.1 Fruit and vegetable byproduct utilization setup.

about by-products and their utilization is necessary for economic modeling to determine the feasibility of new products or transformation to produce a commercially sound business outcome. There are several steps or strategies involved (Fig. 7.1). The first and foremost strategy is assessment. For enabling successful sustainable fruit and vegetable by-products utilization, the type and magnitude of by-products have to be assessed. With the knowledge of by-products and their location in the supply chain, the development of a strategic plan can be started. Second, implementation of the plan needs to have several strategic factors like newer market opportunities, market trends, current market status, and competitive product in the marketplace. Fig. 1 presents the flow of the strategic process for sustainable utilization of by-products. Each phase has to carefully monitor product development. An innovation-based manufacturing company must consider commercial opportunities based on a well-thought-out growth strategy. Packaging and distribution for developed products need to protect the copyright and market share from competitors. Finally, any products which enter into the market need to be economically and ecologically sustainable (Fig. 7.1).

7.7 Conclusion, opportunities, and future challenges

The sustainability of fruit and vegetable by-products is one of the greatest challenges to society globally. The nutritional deficiency faced by society gets remedial compost with fruit and vegetable by-products which might the current top priority. These by-products, when utilized properly, are able to serve as biological potentials of biomolecules to achieve socioeconomic and environmental benefits. Currently, by-products derived from processed fruits and vegetables have limited commercial exploitation, despite having considerable dietary fiber and bioactive compound contents and important biological, antioxidant, antimicrobial, and antiinflammatory, activities. The demand for safe and health-promoting products for a sustainable society, and the incorporation of bioactive extracts or powders to fortify foodstuffs are gaining huge interest within the scientific and commercial communities. Its chemical characterization and specific utilization are the target, whereas modern methods of extraction and commercialization are an important area of current discussions. In addition, a value-added diversified productive food chain may create opportunities in terms of employment and impacts on the social and economic wellbeing of individuals and the national economy. The utilization of sustainable fruit and vegetable by-products needs more novel and innovative techniques to accomplish advanced retrieval rates of bioactive compounds. These extracted biomolecules can be utilized in the developments of functional food, pharmaceuticals, cosmeceuticals, chemical entities, and commercial products.

High-value products and demand for by-product utilization from fruits and vegetables have stimulated research into developing new sources of by-products from unexploited sources. Easily available fruit and vegetable processing by-products can contribute to generating value-added pharmaceutical or food products and also has implications for reducing solid waste and helping to ensure ecological sustainability. Fruit seeds are currently a very insignificant waste which are often discarded after consumption or during processing, which could be explored in the future with advanced extraction and formulation techniques.

Therefore by-product transformation into valuable products makes it possible for fruit and vegetable processing companies to improve their competitiveness. Amongst the possible uses for these materials that can be found in the food industry are as antioxidants, antimicrobials, flavorings, colorants, texturizers, and sources of dietary fiber and proteins, etc. Such a changed setup will assist fruit and vegetable processing companies to reduce their costs, and even to generate additional profits from what was previously considered to be waste, and thus improve their competitiveness. The combined efforts of waste minimization during the production process, environmentally friendly preservation of the product, and utilization of by-products would substantially reduce the amount of waste, as well as boost the environmental profile of the fruit and vegetable processing industry. The fruit and vegetable by-products should be further utilized as a potential source of functional food ingredients, natural antioxidants, antimicrobial compounds, and, in addition, they could be further processed into therapeutic functional food products rather than being discarded as waste.

The global population is expected to increase multifold by the year 2100 (to about 11.2 billion). Addressing the food security of such a huge population and also tackling the environmental issues is a serious challenge. Waste reduction and the reutilization of food resources are important strategies to be developed in this regard. Fruit and vegetable by-products can be utilized, recovered, and converted into value-added food products. Therefore the valorization of these by-products through innovative drying technology and extraction methods could help to produce moisture-protected or dehydrated nutraceutical products for the market. Such steps may create more economic opportunities, along with social and environmental value for the producers, processors, and consumers.

Overall, it is important to remember that the economic feasibility of products is largely dependent on the yield (extract), quality, and market value, although the yield of valuable compounds from food and vegetable by-products is a subjectively small fraction of its total weight. Another area of high growth indicated in the nutraceutical market with sustained market demands. Hence, it is essential to innovate and identify a universal process design that can be used to develop and market products developed from fruit and vegetable by-products.

It is recommended to utilize more novel techniques with respect to by-products to achieve higher rates of bioactive retrieval and, furthermore, valorization of extracted bioactives in food, pharmaceuticals, cosmeceuticals, and chemical industries, through food research and the development of functional foods, etc.

Acknowledgments

The authors are grateful to the Principal, Sri Adichunchanagiri College of Pharmacy and Adichunchanagiri University for facilitating the completion of this chapter and especially acknowledge their families for their constant support and encouragement.

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Chapter 5

Valuable bioactives from vegetable wastes

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5.1 Introduction

Living organisms survive and exist on the Earth by deriving their food either from plant or animal source. In fact, the quantum of food derived from plants is significantly higher when compared with food derived from animals. Food derived from plants, in the form of fruits, vegetables, grains, cereals, etc., are vital in fulfilling the daily nutritional requirements of humans. Vegetables are defined as edible parts of plants including stems and stalks, roots, rhizomes, tubers, bulbs, leaves, flowers, fruits and seeds that are consumed either raw as salad or cooked with the main dish or in a mixed dish (IARC Handbooks of Cancer Prevention, 2019). Globally, a wide range of vegetables is cultivated based on the environmental requirements of the plant, global demand, and the economical aspects. These vegetables are classified by various methods, such as, based on plant parts used as vegetables, based on culture, based on season, and based on the life cycle. Among all these methods of classification, classification of vegetables based on the part of the plant used is widely followed globally (Table 5.1; Fig. 5.1).

5.1.1 Ranking of vegetables

In each and every part of the world, vegetables are grown mainly as a valuable source of nutrition. In addition, with the increase in the global population, the demand for food materials in the form of vegetables, fruits, and cereals has also increased. The global production of fruits and vegetables is in an increasing trend of almost 10% every year (Panda et al., 2016). Cultivation of vegetables mainly depends on the climatic conditions, geographical location, soil, market demand, etc. The top vegetables produced globally include tomatoes, onions, cucumbers, gherkins, cabbages, brassicas, eggplants, carrots, turnips, chilies, peppers, garlic, pumpkins, squash, gourds, cauliflowers, broccoli, spinach, beans, peas, maize, asparagus, cassava leaves, artichokes, etc. The demand for vegetables is increasing every year by approximately by 30%. Tomatoes, potatoes, onions, garlic, and watermelon account for around 66% of total vegetable production globally (Camargo Filho & Camargo, 2017). The details of the top consumed vegetables and the top producers of vegetables are given in Table 5.2.

5.1.2 Top producers of vegetables

As mentioned earlier, each region of the world is blessed with the ideal climatic conditions and various factors required for the production of different types of vegetables. As indicated in Table 5.2, the top 10 leading producers of these fresh vegetables include China followed by India, the United States, Turkey, Nigeria, Vietnam, Mexico, Egypt, Iran, and the Russian Federation. In America, around 29% of crops are fruits and vegetables (Lucier, Pollack, Ali, & Perez, 2006). Asia dominates the fruit and vegetable market with a share of 74.7% (Dias, 2010). Europe is one of the largest importers of fruits and vegetables and accounts for around one-third of world trade (Galanopoulos et al., 2009).

5.1.3 Benefits of consuming vegetables

The American Dietary Association recommends having at least five servings of vegetables based on a 2000 kcal diet in the regular human diet (McGuire, 2011). This is mainly due to the ability of vegetables to supply various vitamins, minerals, and other nutrients along with the nonnutrient secondary metabolites that are required for growth and development and which contribute to the prevention of various diseases (Abu et al., 2020). In countries where malnutrition cases are rising, this can be overcome with the appropriate use of vegetables and fruits. Consumption of fruits and vegetables on a regular basis is associated with health benefits owing to the presence of nutrients and a variety of biologically active, non-nutritive compounds known as phytochemicals.

Valorization of Agri-Food Wastes and By-Products. DOI: https://doi.org/10.1016/B978-0-12-824044-1.00003-9

TABLE 5.1 Various types of fruits and vegetables.

Parts of vegetables	Names of vegetables
Leafy vegetables	Cabbage, cassava, lettuce, spinach, parsley, leaf beet, amaranth, fenugreek leaf, coriander leaf, horseradish leaf, moringa leaf, Murray leaf, etc.
Stem vegetables	Asparagus, celery, cauliflower, *Centella asiatica*, *Basella alba*, etc.
Fruits as vegetables	Tomato, eggplant, pumpkin, cucumber, gherkins, chili, Bell pepper, capsicum, melons, gourds (bitter gourd, bottle gourd, ridge gourd, ivy gourd, and snake gourd), summer squash, ladyâ™s fingers, etc.
Pods	Pea (cowpea, snow pea, chickpea, etc.), beans (French bean, Dolichos bean, broad bean, cluster bean, lima bean, winged bean, red bean, kidney bean, etc.)
Flowers	Broccoli, cauliflower, etc.
Roots	Radish, turnip, carrot, beetroot, yam, sweet potato, parsnip, etc.
Bulbs	Onion, garlic, etc.
Shoots/sprouts	Bamboo shoots, kidney bean, mung bean, pea, soybean sprouts, etc.

Source: IARC Handbooks of Cancer Prevention, 2019.

In addition, the inclusion of fruits and vegetables in the diet may reduce the risk of cancer by 15%, cardiovascular disease by 30%, and overall mortality by any cause by 20%. In addition, vegetable consumption is helpful in overcoming various neurological disorders, inflammation, and diseases associated with deficiencies of vitamins and minerals. The therapeutic benefits of vegetables are mainly due to the presence of various antioxidative phytobioactives like ascorbic acid, vitamin E, carotenoids, polyphenols, and other phytochemicals found in fruits and vegetables (Dias, 2012; Gupta & Prakash, 2009; Prior & Cao, 2000; Yahia, 2010).

5.1.4 Production of vegetable wastes and byproducts

Various cultivated vegetables and fruits either go to the fresh market where they will be used as fresh or cooked food, or processing industries for the preparation of juices, canned food, etc. Some vegetables like broccoli, cauliflower, and asparagus are cultivated for both purposes. In many cases, vegetables and fruits which are cultivated for the fresh market, if they do not match the required quality or demand, are utilized for processing (Lucie et al., 2006). In India, around 30%−40%, that is, around 50 million tons of fruits and vegetables (Sridevi & Ramanujam, 2012), are discarded as waste, whereas in South Africa it is around 47% of total food waste (Oelofse & Nahman, 2013) and in the United States it is around 40% per annum (Gunders, 2012). Overall, around 52% of the total production of fruit and vegetables is lost as waste in the United States, Canada, Australia, and New Zealand. Globally, around 7% of the planted vegetable and fruit crops are not harvested annually, and around 20% of losses occur during production and harvesting (Panda et al., 2016). The amount of waste generated in terms of million tons per year is lower in developed countries like the United States, the United Kingdom, Canada, Australia, and Denmark, than developing countries like India, China, Brazil, and South Africa. Among the food wastes generated, cereals contribute the most, followed by potatoes, fruit, rice, tomatoes, onions, coconut, and pulses (Paritosh et al., 2017).

In the case of food-processing industries, around 30%−50% of input materials used for the production of purees, juice, pickles, sauce, jams, canned food, etc. contribute to fruit and vegetable waste (Di Donato et al., 2011). In America, 50% of the total production of vegetables is sent for processing. In most cases, these vegetable wastes are also considered as byproducts as most can be recycled as valuable products for various industries as they are still rich in a huge amount of primary and secondary metabolites with potential health benefits (Larrosa et al., 2002). The vegetable wastes exist during the entire food supply chain, starting from their cultivation stage, collection, on-field processing, industrial processing, trade, and its domestic handling. The waste generated from fresh fruits and vegetables tops the overall food wastes and the amount of food waste is expected to increase significantly in the coming years due to the increasing global population and economic growth (Galanakis, 2012). The various reasons behind the production of vegetable waste include post-harvest losses due to either on-farm or off-farm wastes, other than the waste produced by food-processing industries. The important causes of on-farm vegetable waste production include the improper stage of harvesting

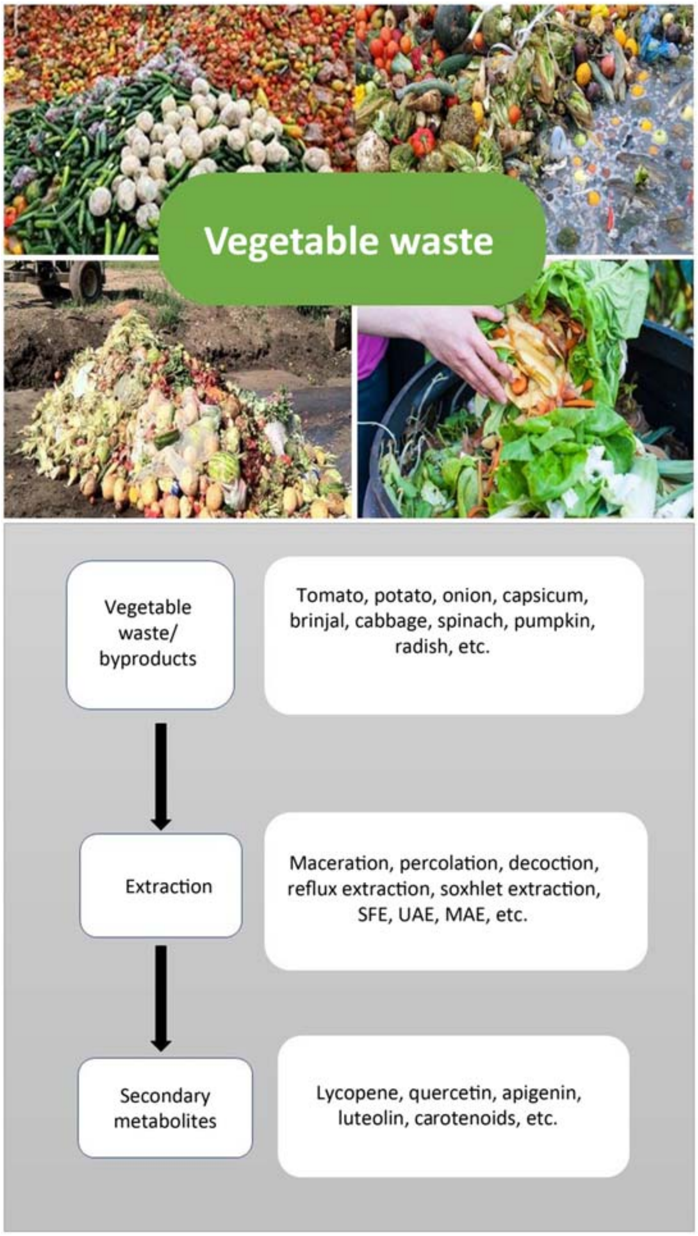

FIGURE 5.1 Phytobioactive byproducts and their uses.

(either before the maturation or after over-ripening of fruit and vegetables), excessive heat while collecting the vegetables, low-quality or inadequate packaging materials, overloading of vegetables in containers, use of unscientific containers for harvesting, and poor farm sanitization. Similarly, off-farm vegetable waste production is due to inappropriate transportation systems, longer duration of the transportation of vegetables, low number of vegetable processing or preserving industries, in addition to the lack of current market information (Arah, Amaglo, Kumah, & Ofori, 2015; Moneruzzaman et al., 2009).

It has been estimated that around 20% of vegetable losses are mainly due to transportation delays and bad road infrastructure, which cause excessive vibration and movement, leading to the mechanical damage of vegetables and fruits (Babatola et al., 2008). Poor storage facilities like warm or humid conditions as well as the presence of rodents and microbial growth in the storage area will also result in the production of vegetable wastes. In addition, several vegetables are selected based on their color, flavor, texture, and size, and if the vegetables fail to meet these requirements then they will be either utilized in the food-processing industries or considered as vegetable waste.

The last few decades have witnessed tremendous growth in food-processing industries globally and the sum of wastes generated by these industries is approximately 20% of the overall production of fruits and vegetables. Around 25%–30% of waste generated from vegetables and fruits includes

TABLE 5.2 Some of the top consumed vegetables and their producers.

Names of top vegetables produced globally in MMT	Top producers of vegetables (MMT)
Tomatoes (182.26)	China (548.99)
Onions (96.77)	India (128.24)
Cucumbers and gherkins (75.22)	United States (31.74)
Cabbages and brassicas (69.38)	Turkey (24.14)
Eggplants (54.08)	Nigeria (16.39)
Carrots and turnips (40)	Vietnam (16.32)
Chilies and peppers (36.77)	Mexico (31.74)
Garlic (28.49)	Egypt (15.57)
Pumpkin, squash, and gourds (27.64)	Iran (15.07)
Cauliflower and broccoli (26.5)	Russian Federation (13.71)

MMT, Million metric tons.

the skin, pomace, rind, peels, pods, leaves, seeds, etc. For example, the edible parts of the carrot, potato, tomato, and papaya are around 60%−70%, 60%−85%, 9%−97%, and 53%, respectively, and the byproducts of carrot (pomace), potato (peel), tomato (peel and seeds), and papaya (peel, seed, and unusable pulp) are around 30%−40%, 15%−40%, 3%−7%, and 47%, respectively (Barbulova et al., 2015; Saini et al., 2019). In the case of potato, its consumption as a vegetable has decreased, and instead there has been a considerable increase in processed potato products like French fries, chips, Pringles, and puree. Hence, in the potato-processing industries around 10% is sorted out due to poor quality and 10% is lost due to the removal of peels, which are an important source of phenolic acids like chlorogenic acid, gallic acid, caffeic acid, and protocatechuic acid. In the case of onions, Europe produces around 450,000 tons of onion waste each year, which consists of brown skin, the outer two fleshy leaves, and the tops, which are all considered as sources of flavonoids (Dias et al. 2020). This is similar for tomatoes, carrots, beetroots, etc. Overall, processed foods industries constitute around 25% of the generation of organic waste consisting of peel, stem, seeds, and pomace. The top producers of food wastes include China, India, the United States, and the Philippines (Saini et al., 2019). Vegetable losses for various reasons by producing countries will lead to an increase in the price of fresh vegetables among the dependent countries, as well as the processed product price being increased many-fold due to the lack of availability of the vegetables. This will not only become expensive for consumers but also harms the economy of dependent countries. These vegetables and fruits are rich in various vitamins like ascorbic acid, riboflavin, provitamin A, and minerals like calcium, iron, etc., where the lack of availability for a long duration can lead to the occurrence of diseases associated with vitamin and mineral deficiencies. In addition, it may lead to the closure of vegetable-dependent food processing industries and lead to unemployment (Dolan & Humphrey. 2000).

Improper disposal of vegetable waste and combustion leads to environmental pollution with the release of dioxins which are hazardous. Land filling of these vegetable wastes also causes water and air pollution, and leads to the emission of methane gas that has an adverse impact on the environment (ElMekawy et al. 2015).

5.1.5 Measures undertaken to minimize vegetable wastes

There are various ways through which the occurrence of vegetable wastes can be minimized. These include the cultivation of vegetables based on the soil and climatic requirements, since farmers often grow plants in soil which is not suitable for their growth and development. The utilization of organic fertilizers and pesticides can attract consumer demand, while the presence of synthetic pesticides on vegetables reduces consumer acceptance. In the case of perishable fresh vegetables like tomatoes, leafy vegetables, etc. exporting or transporting to long-distance localities or countries through regular transportation modes like trucks, ships, or train should be avoided. Instead, they can be transported by air, based on the cost of the vegetables and demand, in order to maintain the vegetables' quality and integrity. If farmers are targeting a distant market for tomatoes or other fruit vegetables then they must harvest them in a mature green state, rather than after ripening, to avoid vegetable waste (Moneruzzaman et al., 2009). Even while harvesting soft vegetables, the containers used must not be hard with sharp surfaces that may cause mechanical injuries, instead, they should have a smooth surface and be shallow to prevent overloading and mechanical injuries (Arahi et al., 2015).

Other methods to control vegetable waste include maintaining controlled atmospheric conditions like oxygen, carbon dioxide, and nitrogen levels to lower the respiration rate and to extend the shelf-life of perishable fruits and vegetables. Controlled atmospheric techniques also involve maintaining relative humidity, a crucial factor that controls ethylene oxide which accelerates the process of ripening of fresh fruits and vegetables. In addition, it will also maintain the quality, integrity, slow ripening, and retardation of discoloration of fruits and vegetables like lettuce, avocados, tomatoes, asparagus, etc. In the case of tomatoes, if not stored properly then the ascorbic acid present in them is susceptible to oxidation, light, and humidity leading to the loss of the ascorbic acid (Koh et al., 2012). In certain cases, fruits and vegetables are washed with chlorinated water or anolyte water prior to packing in order to reduce the microbial load and maintenance of superior quality during storage (Workneh et al., 2012). Some vegetables like tomato, spinach, lettuce, and potatoes are exposed to UV light radiation with the wavelength of 200−270 nm that causes the inactivation of microorganisms (Escalona et al., 2010; Yaun et al., 2004). Exposure to UV radiation also reduces the inhibition of cell wall degradation in potatoes and so extends their shelf-life (Charles et al., 2009), reduces the rate of decay of onions (Kasim & Ufuk Kasim, 2012), and also prevents the ripening of tomatoes. In the case of leafy vegetables with a high moisture content, they must not be overloaded, instead they should be spread uniformly from the time of harvest till reaching the market.

One more important method to curb vegetable waste generation is the cultivation of vegetables based on consumer demand, or providing farmers with the awareness about the market demand (Huang, 2004). Farmers must also know the shelf-life of vegetables they cultivate as this ensures that they know how long they can preserve the cultivated and harvested vegetables. Educating farmers through various modes of communication about advanced cultivation and harvesting technologies helps avoid the occurrence of vegetable waste. It may be the government's prime duty to safeguard the interests of farmers by regulating the prices for cultivated vegetables and fruits which would support and motivate farmers for cultivation and avoid the occurrence of vegetable waste.

5.2 Valorization of vegetable wastes and byproducts

Vegetable wastes produced during the agricultural process such as cultivation, harvesting, garbling (dressing), that is, on-farm or off-farm, as well as the vegetable byproducts generated by food-processing industries are described as agro-industrial vegetable byproducts. Fruit and vegetable byproducts derived from processing industries as well as the agricultural process are composed of nonedible parts of food (Plazzotta et al., 2017). Improper disposal of vegetable waste rich in moisture content that is highly biodegradable and with a microbial load may lead to environmental hazards due to the release of toxic gases and growth of various microbes leading to environmental pollution and the occurrence of microbe-related infections (Sukla, Pradhan, Panda, & Mishra, 2015). According to Breeze (2018), the anaerobic biological decomposition of organic matter is the third major source of atmospheric methane emission that is equivalent to 800 million tons of CO_2 gas (Breeze, 2018; Ioannis, Abhay, & Pratap, 2010). In order to avoid this, the waste generated from vegetables is processed by various waste management methods and valorization techniques to convert them into feed for livestock, production of compost and fertilizers, as well as processed anaerobically for the production of biogas (Barbulova et al., 2015; Saini et al., 2019).

These byproducts are rich in numerous nutrients, fiber, minerals, and certain vitamins. The important biologically active compounds (bioactives) that exist in abundant amounts include polyphenols, flavonoids, and anthocyanins, in addition to primary plant metabolites like carbohydrates, proteins, and lipids in the vegetables. The term phytobioactives refers to the chemical constituents found in plants with various pharmacological/biological activities along with their nutritional values. Vegetable byproducts are generally employed as nutraceuticals, food ingredients, functional foods, food additives, and in the development of cosmetic products (Rizk et al., 2014). From vegetable wastes and byproducts, various biologically active and valuable chemical constituents are recovered using different extraction and isolation techniques. Hence, all these processes lead to a zero-waste strategy (Saini et al., 2019).

Valorization of vegetable byproducts with the help of various advanced technologies leads to the recovery of a wide array of bioactives with potential therapeutic efficacy from billions of tons of vegetable waste generated. These bioactives may be cheaper, effective, and alternates to the bioactives derived from medicinal plants. This may help in the sustainability of medicinal plants and avoid them becoming endangered (Barbulova et al., 2015). Though a few vegetables like *Momordica charantia*, *Capsicum annum*, etc. contain specific bioactive constituents, most vegetables and fruits, their wastes and byproducts share common bioactives like polyphenols, carotenoids, and anthocyanins, along with the primary metabolites (Table 5.3).

5.2.1 Vitamins

Various vegetables like asparagus, spinach, chives, turnip, and some types of beans such as black beans, kidney

TABLE 5.3 Phytochemicals derived from vegetable byproducts.

Name of the vegetable waste/ by-products	Source	Bioactives	References
Asparagus	*Asparagus racemosus*	Lutein, anthocyanins, β-carotene, quercetin, rutin, phytosterols, vitamin C, vitamin B_6 and folacin.	Hou et al. (2004), Li et al. (2012), IARC Handbooks of Cancer Prevention (2019)
Basella leaf	*Basella alba*	Naringin, apigenin, luteolin, rutin, kaempferol, ascorbic acid, thiamine, vitamin A, folic acid, α-tocopherol and carotenoids.	Baskaran et al. (2015), Deshmukh and Gaikwad (2014)
Broccoli	*Brassica oleraceae* Botrytis cultivar group	Vitamin C, α-carotene, β-carotene, lutein, zeaxanthin, lycopene, quercetin, kaempferol, p-coumaric acid and caffeic acid.	Justesen et al. (1998), Kumar et al. (2017), Mattila and Hellström (2007)
Cabbage	*Brassica oleracea* Capitata cultivar group	Vitamin C, α-carotene, β-carotene, lutein, lycopene, quercetin, kaempferol, anthocyanins, caffeic acid, p-coumaric acid, chlorogenic acid, ferulic acid, sinapic acid, anthocyanins like cyaniding, peonidin and pelargonidin.	Hou et al. (2004), Li et al. (2012), Zuiter (2014), Mizgier et al. (2016)
Carrot	*Daucus carota*	α-carotene, β-carotene, lutein, cryptoxanthin, lycopene, apigenin, myricetin, caffeic acid, p-coumaric acid, chlorogenic acid, sinapic acid, caffeoylquinic acid, ferulic acid and anthocyanins.	Raffo et al. (2002), Mizgier et al. (2016), Bakowska-Barczak (2005)
Carrot pomace	*Daucus carota*	α-carotene, β-carotene, lycopene, vitamin C, E and anthocyanins and phenolic acids.	Majerska et al. (2019), Schieber et al. (2001)
Carrot leaves	*Daucus carota*	α-carotene, β-carotene, omega-3-fatty acids and lutein.	Leite et al. (2011), Perrin et al. (2016)
Cauliflower	*Brassica oleraceae* Botrytis cultivar group	Vitamin C, quercetin, kaempferol, chlorogenic acid, caffeic acid, sinapic acid and *p*-coumaric acid.	Zuiter (2014), Mattila and Hellström (2007)
Celery leaf	*Apium graveolens*	Apigenin, luteolin and apigenin.	Majerska et al (2019), Yang et al. (2008), Justesen et al. (1998)
Cow pea	*Vigna unguiculata*	Quercetin, kaempferol and isorhamnetin.	Yang et al. (2008)
Cucumber peel	*Cucumis sativus*	β-carotene, quercetin and kaempferol.	Zeyada et al. (2008)
Eggplant	*Solanum zuccagnianum*	Quercetin, kaempferol, apigenin, luteolin, anthocyanins, delphinidin, cyanidin, malvidin and petunidin.	Zuiter (2014), Ferarsa et al. (2018)
Garlic husk	*Allium sativum*	Ferulic acid, hydroxybenzoic acid, *p*-coumaric acid, caffeic acid	Kallel et al. (2014)
Green beans	*Phaseolus vulgaris*	Quercetin, kaempferol, apigenin, luteolin, daidzein, genistein, ferulic acid, *p*-coumaric acid and carotenes.	Nemitz et al. (2016), Zuiter (2014)
Lettuce	*Lactua sativa*	Lycopene, zeaxanthin, quercetin, kaempferol, chlorogenic acid, pcoumaroylquinic acid, caffeoylmalic acid, dicaffeoyltartaric acid and chicoric acid.	Ribas-Agustí et al. (2011)

(*Continued*)

TABLE 5.3 (Continued)

Name of the vegetable waste/ by-products	Source	Bioactives	References
Moringa leaves	*Moringa oleifera*	Quercetin, kaempferol, isorhamnetin, nizarin, isoquercitrin, kaempferritin, vitexin, isovitexin, *p*-coumaric acid, chlorogenic acid and gallic acid.	Hamed, Mohammed, & Ahmed (2017), Oldoni et al. (2019)
Moringa seeds	*Moringa oleifera*	Gallic acid, p-coumaric acid, ferulic acid, vainillic acid, caffeic acid, cinnamic acid, quercetin, catechin and epicatechin.	Govardhan Singh et al. (2013)
Murraya leaf	*Murraya koenigi*	Essential oils like caryophyllene oxide, β-caryophyllene, geranyl acetate, myrecene, α-terpene, α-pinene, β-pinene, bornyl acetate, limonene and flavonoids like quercetin, kaempferol, rutin, myricetin and catechins.	Rajendran et al. (2014), Olawore et al. (2005), Rana et al. (2004), Ghasemzadeh et al. (2014), Noolu et al. (2016)
Onion	*Allium cepa*	Quercetin, kaempferol, anthocyanins, caffeic acid and ferulic acid.	Hou et al (2004), Li et al. (2012), Justesen et al (1998)
Parsley	*Petroselium crispum*	Kaempferol, apigenin and luteolin.	Zuiter (2014)
Potato peel	*Solanum tuberosum*	Lycopene, chlorogenic, gallic, protocatechuic and caffeic acids.	Mattila and Hellström (2007), Sagar et al. (2018), Zeyada et al. (2008)
Pumpkin	*Curcubita moschata*	α-carotene, β-cryptoxanthins, zeaxanthin, lycopene, gallic acid, vanillic acid, chlorogenic acid, caffeic acid, procatechuic acid and rutin.	Kulczyński and Gramza-Michałowska (2019a, 2019b)
Raddish root	*Raphanus sativus*	Kaempferol, quercetin, anthocyanins, cyanidins, pelargonidin and caffeic acid.	Krzeminski (1977)
Raddish leaves	*Raphanus sativus*	Kaempferol, quercetin, caffeic acid, p-coumaric acid, ferulic acid, genistic acid and vanillic acid.	Khanam, Oba, Yanase, & Murakami (2012), Strack et al. (1985)
Red beet peel	*Beta vulgaris*	α-carotene, *p*-coumaric acid, ferulic acid, cinnamic acid, vanillic acid, chlorogenic acid, caffeic acid, ellagic acid, quercetin, rutin, kaempferol, myricetin, betaxanthins and betacyanins.	Kujala et al. (2000), Ninfali et al. (2017), Ravichandran et al. (2012), Koubaier et al. (2014)
Red beet pomace	*Beta vulgaris*	Polyphenols like ferulic acid, cinnamic acid, vanillic acid, chlorogenic acid, betacyanins and betaxanthins.	Majerska et al (2019), Ravichandran et al (2012)
Red beet leaf	*Beta vulgaris*	α-carotene, beta cyanins, beta xanthins, ferulic acid, apigenin and vitexin.	Bengardino et al. (2019), El-Ghaffar et al. (2019)
Red pepper	*Capsicum annuum*	Vitamin C, α-carotene, lycopene, zeaxanthin, quercetin, luteolin, caffeic acid and capsaicinoid alkaloid.	Majerska et al. (2019), Tundis et al. (2011)
Spinach leaf	*Spinacia oleracea*	Vitamin C, β-carotene, lutein, violaxanthin, neoxanthin, zeaxanthin, isorhamnetin, chlorogenic acid, ferulic acid, p-coumaric acid, procatechuic acid, quercetin, kaempferol, myricetin, apigenin and luteolin.	Kidmose et al. (2001), Dehkharghanian et al. (2010), Mattila and Hellström (2007)
Squash	*Curcubita pepo*	α-carotene, β-carotene, zeaxanthin, lutein, gallic acid, vanillic acid, chlorogenic acid, caffeic acid, procatechuic acid and rutin.	Raffo et al. (2002), Milani et al. (2017), Kulczyński and Gramza-Michałowska (2019a, 2019b)

(*Continued*)

TABLE 5.3 (Continued)

Name of the vegetable waste/ by-products	Source	Bioactives	References
Sweet potato waste	*Ipomoea batatas*	β-carotene, lutein, quercetin, caffeic acid, chlorogenic acid, anthocyanins tocopherols	Raffo et al. (2002), Okuno et al. (2002), Bakowska-Barczak (2005)
Turmeric leaf	*Curcuma longa*	Essential oils like, p-cymene, α-phellandrene, terpinolene, cineole, linalool, geraniol and myrecene.	Sindhu et al. (2011), Ananya, Sujata, Panda, & Sanghamitra (2009)

beans, navy beans, soybeans, as well as chickpeas and green peas, are rich in vitamin folacin. Vitamin C is found in enormous quantities in vegetables like broccoli, cabbage, cauliflower, spinach, red and green pepper, tomato, and papaya (Ruiz-Rodriguez et al. 2008; Shibata et al. 1992; Uusiku et al. 2010).

5.2.2 Carotenoids

Carotenoids are tetraterpenes and are also known as fat-soluble pigments. There are more than 600 carotenoids found in nature. Among them, only 40 carotenoids are found in the human diet. Carotenoids are grouped as provitamin A carotenoids like β-carotene and β-cryptoxanthin, and nonprovitamin A carotenoids like lutein and lycopene. It is also reported that vegetables that are rich in chlorophyll are also rich in beta-carotene (Gerster, 1997). The commonly used extraction technique for the extraction of carotenoids includes maceration, ultrasound-assisted extraction (Luengo et al. 2014), and enzyme-assisted extraction (EAE) (Ghosh & Biswas, 2016). Carotenoids like α-carotene are found in asparagus, beet greens, broccoli, cabbage, spinach, carrot, cassava leaves, pumpkin, squash, turnip leaves, red pepper (Table 5.4). β-Carotene imparts orange color to carrots, squashes, tomatoes, and sweet potatoes and is considered as the important precursor of vitamin A. It is converted into retinol, which has an important role in vision and one of the important sources of β-carotene is tomato (Raffo et al., 2002). Carotenoids like β-cryptoxanthins are present in significant amounts in tomato, squash, pumpkin, corn, broccoli, and red pepper. As indicated in Table 5.4, lutein is found in high quantities among vegetables like asparagus, tomato, spinach, sweet potato, and corn, and helps in the preservation of visual function by protecting the macular of human eyes and offers protection against various cardiovascular diseases by inhibiting NF-κβ signaling (Perry et al., 2009; Riccioni et al., 2012; SanGiovanni et al., 2007). Lycopene is found in high quantities in tomato, broccoli, cabbage, carrot, corn, lettuce, potato, pumpkin, spinach, tomato, and sweet and red pepper, whereas zeaxanthin is found commonly in spinach, red pepper, corn, lettuce, and turnip greens (IARC Handbooks of Cancer Prevention Volume 8: Fruits and Vegetables. Chapter 1, Definition and classification of fruits and vegetables; Dias et al., 2020). As indicated in Table 5.4 lycopene offers protection against various cancers and osteoporosis through antioxidant activity and downregulation of proinflammatory cytokines, TNF-α and interleukin-6 (Markovits & Levy, 2009; Rao et al., 1999; Sahni, et al., 2009).

5.2.3 Flavonoids

Flavonoids are water-soluble secondary metabolites which come under the group of glycosides and are present in the cytosol and stored in the plant cell vacuole. To date, there have been more than 7000 flavonoids identified from plants and the number continues to increase as they are found to possess a wide array of pharmacological potentials. Table 5.4 presents the therapeutic potency of flavonoids that includes antioxidant, anti-inflammatory, anti-nociceptive, anti-cancer, cardioprotective, antidiabetic, hypo-lipidemic, anti-atherosclerotic, nephro-protective, immunomodulatory activities, and also to treat neurodegenerative disorders (Cassidy & Kay, 2012; Chávez-González et al., 2020; Verhoeyen et al., 2002). Flavonoids are categorized into six classes based on their structures, which vary slightly among each group that includes flavonols, flavones, isoflavones, flavanones, flavan-3-ols, and anthocyanins (Zuiter, 2014). Generally, flavonoids are extracted by maceration (Bahorun et al., 2004), refluxation (Zhu et al., 2010), ultrasound-assisted extraction (Prasad et al., 2009), Soxhlet extraction (Hartonen et al., 2007; Zhu et al., 2010), supercritical fluid extraction (Bimakr et al., 2011), accelerated solvent extraction (Ko et al., 2011), microwave-assisted extraction (Jha et al., 2017), and EAE (Kumar et al., 2017). Various root (carrot, beet root, turnip), rhizome (ginger, turmeric), and fruit (capsicum, tomato, etc.) producing vegetables after harvesting have other parts of the plant that will be disposed of as vegetable waste. Similarly, byproducts obtained from the vegetable industries are also disposed of as waste. These are rich in flavonoids and can be utilized either as feed for animals, a coloring agent, or

TABLE 5.4 Bioactivity of selected phytobioactives.

Phytobioactives	Biological activities	References
Carotenoids		
α-carotene	Antioxidant, anti-carcinogenic properties, enhances immune function and reduces the occurrence of type II diabetes in men.	Li et al. (2011), Sluijs et al. (2015), Milani et al (2017)
β-carotene	Antioxidant properties, the inhibition of malignant tumour growth and the induction of apoptosis, to treat neuroblastoma cancer stem cells. It also helps in the treatment of complications associated with vision as a A precursor of vitamin A, improved cognitive function in elderly patients, reduced occurrence of type diabetes in men, reduced arsenic induced toxicity in mice, hepatoprotective and shown antikeratopathy as well as amelioration of corneal changes in diabetic rats.	Milani et al. (2017), Abdul-Hamid & Moustafa (2014), Das et al. (2015), Raffo et al. (2002), Peng et al. (2013), Lee et al. (2013), Li et al. (2015)
Lycopene	Anticancer, treat osteoporosis, antioxidant, down regulate pro-inflammatory cytokines like IL-6, TNF-α and cardioprotective in type II diabetic patients.	Sahni et al. (2009), Fuhrman et al. (2000), Rao et al. (1999), Markovits and Levy (2009), Shidfar et al. (2011)
Lutein	Maintain visual function, protect the macular of the eyes, various age related eye diseases, cardioprotective action through the inhibition of NF-KB, hepatoprotective and protective against prostate cancer cells.	SanGiovanni et al. (2007), Riccioni et al. (2012), Krinsky et al. (2003), Madaan et al. (2017), Moeller et al. (2006), Rafi et al. (2015)
Zeaxanthin	Visual disorders such as age-related macular degeneration, age-related cataract, ischemic/hypoxia induced retinopathy, light damage of the retina, retinitis pigmentosa, retinal detachment, diabetic retinopathy and cognition diseases.	Jia et al. (2017), Milani et al. (2017), Moeller et al. (2006)
Cryptoxanthin	β-cryptoxanthin inhibit the osteoclast like cell formation in mouse marrow, prevents bone loss, reduces osteoarthritis, chemopreventive against gastric cancer, ameliorates neurothic pain, alleviate steatohepatitis and shows cardioprotective effect by inhibiting NF-κB -mediated inflammatory signals.	Uchiyama and Yamaguchi (2004), Ozaki et al. (2015), Kobori et al. (2014), Zhang et al. (2020), Gao et al. (2019), Park et al. (2017)
Phenolic acids		
Gallic acid	Antiatherosclerotic through the inhibition of platelet aggregation, cardioprotective effect, reduces lindane induced cardiotoxicity in rats, cardioprotective in diabetes induced myocardial dysfunction, anti-inflammatory, reduces the lipid and glucose level, antidiabetic activity, chemoprotective and antitumor effect in lung cancer cells.	Chang et al. (2012), Moon et al. (2012), Padma et al. (2013), Patel and Goyal (2011), Choi et al. (2009), Bak et al. (2013), Latha and Daisy (2011), Giftson et al. (2010), Kawada et al. (2001)
Ellagic acid	To treat colon cancer, prostate cancer in SCID mouse tumor model, exhibit cardioprotective effect through antidyslipidemic, anticoagulatory and antioxidative mechanism.	Päivärinta et al. (2006), Umesalma et al. (2015), Wang et al. (2014), Chao et al. (2009)

(*Continued*)

TABLE 5.4 (Continued)

Phytobioactives	Biological activities	References
Vanillic acid	antioxidative, anti-mutagenic, anti-cancer, neuroprotective activities, anti-inflammatory, antinociceptive activity, cardiac protection in rats through its free radical scavenging, antioxidant and anti-inflammatory process, offers neuroprotective effect to treat neurodegenerative disorders through antioxidant mechanism and antiallegeric effect through the inhibition of proinflammatory cytokines.	Mathew et al. (2018), Leal et al. (2011), de los Angeles Yrbas, Morucci, Alonso, & Gorzalczany (2015), Stanely Mainzen Prince et al. (2011), Singh et al. (2015), Jeong et al. (2018)
Procatechuic acid	Inhibition of atherosclerosis in vascular smooth muscles, inhibited the cytotoxicity, apoptotic morphology, anticoagulant, and antioxidative. antiviral, antiatherosclerotic, hyperlipidemic, and ischemic heart disease protective, antihypertensive, hepatoprotective and anti-inflammatory.	Kakkar and Bais (2014), Zhou et al. (2005), Zhou et al. (2012), Liu et al. (2002)
Caffeic acid	Cardioprotective activity through antidyslipidemic, anticoagulatory and antioxidative mechanism, to treat hepatocarcinoma, antinociceptive effect by increasing the latency of tail flick and exhibited antidementia effect in aluminium chloride induced dementia in rats.	Chao et al. (2009), Monteiro Espíndola et al., (2019),Gamaro et al. (2011), Khan et al. (2013)
Ferulic acid	Antioxidant, antiinflammatory, antimicrobial, antiallergic, hepatoprotective, anticarcinogenic, antithrombotic, increase sperm viability, antiviral and vasodilatory actions, metal chelation, modulation of enzyme activity, activation of transcriptional factors, gene expression and signal transduction.	Kumar et al. (2017), Mancuso and Santangelo (2014)
Sinapic acid	Cardioprotective effect through attenuating fibrosis and oxidative stress, antiinflammtory effect through the suppression of inflammatory biomarkers and antidyslipidemic.	Silambarasan et al. (2014), Yun et al. (2008), Roy and Mainzen Prince (2013)
p-coumaric acid	Antioxidant, anti-cancer, antimicrobial, antivirus, anti-inflammatory, antiplatelet aggregation, anxiolytic, antipyretic, analgesic, anti-arthritis activities, antiobesity, hypolipidemic and antidiabetic activity.	Pei et al. (2016), Scazzocchio et al. (2011)
Chlorogenic acid	Antidiabetic activity by increased glucose uptake through increased expression of GLUT-4 and PPAR- transcription, decreased hepatic glucose and fatty acid synthesis, exerts antiamnestic activity through the inhibition of acetylcholinesterase and malondialdehyde and inhibited benign prostatic hyperplasia in animal model.	Prabhakar and Doble (2009), Ong et al. (2013), Kwon et al. (2010), Huang et al. (2017)
Flavonoids		
Quercetin	Anti-inflammatory and inhibit LDL oxidation, possess anti-inflammatory, antihypertensive, vasodilator effects, anti-obesic, antihypercholesterolemic and anti-atherosclerotic activities, antihypertensive, apoptosis in human myeloid leukemia cells, attenuates diabetic nephropathy in rats and hypoglycemic effect.	Chopra et al. (2000), Salvamani et al. (2014), Perez-Vizcaino et al. (2009), Duraj et al. (2005), Anjaneyulu and Chopra (2004), Vessal et al. (2003)

(*Continued*)

TABLE 5.4 (Continued)

Phytobioactives	Biological activities	References
Rutin (quercetin 3-O-rutinoside)	Anti-inflammatory, antibacterial, antiviral, antiprotozoal, antitumor,inhibit LDL oxidation, antiallergic, antiplatelet, cytoprotective, vasoactive, antispasmodic, and antihypertensive. Hypolipidaemic and nephroprotective activities.	Patel and Patel (2019), Umarani et al. (2015), Sadeghnia et al. (2013)
Kaempferol	Antioxidant and anti-inflammatory, cardioprotective and antihypertensive, antinociceptive, anti-inflammatory and induces apoptosis of human lung carcinoma cells.	Devi et al. (2015), Dabeek and Marra (2019), De Melo et al. (2009), Leung et al. (2007)
Naringenin	Antidiabetic, antioxidant, peroxisome proliferator-activated receptors (PPARs) activator, hypolipidaemic, antiatherogenic, cardioprotective, apoptosis of prostate cancer cells and immunomodulator.	Nyane et al. (2017), Lim et al. (2017), Zeng et al. (2018)
Myricetin	Hypoglycemic, antidiabetic effect, analgesic, anti-inflammatory, cytotoxic effect, anti-oxidantive, anticancer, displays several beneficial effects to protect against diseases such as Parkinson's and Alzheimer's.	Ong and Khoo (2000), Liu et al. (2006), Tong et al. (2009), Wang et al. (2010), Dimas et al. (2000), Semwal et al. (2016)
Apigenin	Antibacterial, antiproliferatives, anticancer agent, antidepressant, hepatoprotective, cardioprotective and antidiabetic agent.	Liu et al. (2013), Yan et al. (2017), Yi et al. (2008), Zhou et al. (2017)
Luteolin	Antioxidative, anti-inflammatory, antiallergic, antidiabetic and neuroprotective.	Seelinger et al. (2008), Hirpara et al. (2009), Nabavi et al. (2015)
Vitexin	Anticancer, antioxidant, anti-inflammatory, antidepressant, anticonvulsant, anxiolytic, neuroprotective, antinociceptive, cardioprotective and antidiabetic.	He et al. (2016), de Oliveira et al. (2020)
Catechins	Antioxidant, antispasmodic, bronchodilator, vasodilator, neuroprotective and to treat age related cognitive diseases.	Ghayur et al. (2007), Mandel and Youdim (2004), Farzaei et al. (2019)
Daidzein	Antiproliferative, antioxidative, antiallergic and anticancer activities.	Choi and Kim (2013), Shimoda and Hamada (2010), Hua et al. (2018)
Hesperetin	Antioxidative, vasorelaxant, antinociceptive, anticancer and neuroprotective.	Orallo et al. (2004), Loscalzo et al. (2011), Zhang et al. (2015), Cho (2006)
Anthocyanins (pelargonidin, cyanidin, delphinidin, malvidin, peonidin and petunidin)	Antioxidative, anticancer, to treat cardiovascular diseases and age related degenerative diseases.	Hou et al. (2004), Li et al. (2012)

substrate for the production of biomass, enzymes, organic acids, bioelectricity, etc. (Agcam et al., 2017; ElMekawy et al., 2015; Wobeto et al., 2006; Yang & Ling, 1989).

Flavonols are the most commonly found flavonoids of all categories of plants including fruits, vegetables, and many medicinal plants. The important flavonols found in vegetables include quercetin (broccoli, cabbage, red onion, sweet potato, tomato, string bean, chives, lettuce, red pepper, chives), kaempferol (broccoli, cabbage, onion, tomato, green bean, chives, horseradish, lettuce, red pepper, chives), myricetin, and isorhamnetin, and are of a variety of colors ranging from white to yellow (Rybarczyk-Plonska et al., 2016). Quercetin is found to have inhibited LDL oxidation through antioxidant mechanism (Chopra et al., 2000). Flavanols are also known as flavan-3-ols and various phytochemicals of this group include catechins, epicatechins, and gallocatechins, and are considered as a most complex class of flavonoids because of their size and their existence either as monomers called catechins, or polymeric catechins called condensed tannins (Zuiter, 2014).

Flavones are found in most parts of the plant including the stem, leaves, bark, heartwood, flower, fruits, seeds, roots, and rhizomes. Some important vegetables found to contain flavones include carrot, celery, parsley, and red and green pepper (IARC Handbooks of Cancer Prevention (Vol. 17), 2019), and the important flavones include apigenin (carrot and celery), luteolin (red and green pepper), and vitexin (Martens & Mithöfer, 2005; Olagaray & Bradford, 2019). *Isoflavones* are a group of flavonoids and are commonly referred to as phytoestrogens and include daidzein and genistein. They are widely employed in various fields including nutrition, medicine, and cosmetics (Cassidy & Kay, 2012). They are normally distributed among the plants of the Leguminosae family, such as soybeans and red clovers (Nemitz et al., 2016). *Flavanones* are also known as dihydroflavones and are found in aromatic plants like mint, citrus fruits, and tomatoes (Zuiter, 2014). Some of the important flavanones include naringenin, hesperetin, and eriodictyol and they are found in either glycosidic form or in the form of aglycones (Cassidy & Kay, 2012).

Anthocyanins are also known as anthocyanidins and are responsible for the colors (blue, red, pink, and purple) of leaves, vegetables, fruits, and flowers. There are more than 500 anthocyanins present in plants and some of the important anthocyanins include pelargonidin (red), cyanidin (magenta), delphinidin (purple), malvidin (purple), peonidin (magenta), and petunidin (purple) (Zuiter, 2014; Da Silva et al., 2014). Anthocyanins are normally found in vegetables like asparagus, sweet potato, purple carrot, red cabbage, red onion, red bean, etc. (Table 5.4). As indicated in Table 5.4, anthocyanins offer protection against various types of cancers, cardiovascular diseases, and age-related degenerative diseases through an antioxidant mechanism by inhibiting various free radicals (Hou et al., 2004; Li et al., 2012; Mizgier et al., 2016). The addition of such types of phytobioactives not only improves the color of any product, it also ensures preservation of the formulation and protection against various free radical-induced diseases (Mizgier et al., 2016). Various dairy products, desserts, and fruits, as well as vegetable beverages, can be imparted with color using these anthocyanins. Exposure to light for a long time as well as a higher temperature may cause the degradation of anthocyanins, resulting in the color fading. Hence, care must be taken while processing and preserving such products (Bakowska-Barczak, 2005). Anthocyanins are generally extracted by maceration solvent extraction, microwave-assisted extraction (Liazid et al., 2011), and EAE (Maier et al., 2008).

5.2.4 Phenolic acids

Phenolic acids found in plants are nonflavonoid polyphenolic compounds present in varying concentrations in different parts of the same plant or different plants. Table 5.3 presents the different types of phenolic acids and their sources, whereas Table 5.4 present the therapeutic potency of these phenolic acids. The phenolic acid phytobioactives are grouped under hydroxybenzoic acids, for example, gallic acid, ellagic acid, vanillic acid, protocatechuic acid, gentisic acid, syringic acid, vanillic acid, and 4-hydroxybenzoic acids and hydroxycinnamic acids include caffeic acid (broccoli, red onion, cabbage, carrot, red or green pepper, tomato), ferulic acid (red onion, corn), sinapic acid, chlorogenic acid (ester of hydroxycinnamic acid and quinic acid), and *p*-coumaric acid (Zuiter, 2014). These acids are found in higher concentrations than hydroxybenzoic acid in normal fruits and vegetables, however, in pigmented vegetables like tomato, onion, red cabbage, carrot, sweet potato, black radish, eggplant, spinach, and potatoes, etc., hydroxybenzoic acids are found in higher concentrations (Dias et al., 2020; Lewis et al., 1998). Phenolic acids exert anticancer activity through their antioxidant mechanisms and also stimulate apoptosis of cancer cells and inhibit proliferation (Umesalma et al., 2015). Generally, phenolic acids are extracted by maceration (Bahorun et al., 2004), ultrasound-assisted extraction (Kumar et al., 2017; Pimentel-Moral, de la Luz Cádiz-Gurrea, Rodríguez-Pérez, & Segura-Carretero, 2020), accelerated solvent extraction (Singh & Saldaña, 2011), microwave-assisted extraction (Jha et al., 2017; Szewczyk & Olech, 2017), and even by EAE techniques (Kumar et al., 2017).

Gallic acid inhibits platelet activation and platelet−leukocyte aggregation to show antiatherosclerosis function (Chang et al., 2012; Moon et al., 2012). *Ellagic acid* induced apoptosis and decreased proliferation of HCT-15 colon adenocarcinoma cells (Umesalma et al., 2015) and also exhibited a beneficial effect in a prostate cancer-induced mouse tumor model (Wang et al., 2014). It is also proven to exhibit a cardioprotective effect through antioxidative, antidyslipidemia, anticoagulative, and antiinflammatory properties in diabetic mouse cardiac tissue (Chao et al., 2009). *Caffeic acid* is found in beans and is proved to exhibit a cardioprotective effect through antioxidative, antidyslipidemic, anticoagulative, and anti-inflammatory properties in diabetic mouse cardiac tissue (Chao et al., 2009). *Ferulic acid* is mainly found in legumes, pumpkin, and cereal grains (Mancuso & Santangelo, 2014). *P-coumaric acid* can be found in beans and wheat (Lafay & Gil-Izquierdo, 2008). It is found to inhibit the accumulation of oleic acid-induced triglycerides and also antidiabetic activity by upregulating PPAR-γ (Scazzocchio et al., 2011). Chlorogenic acid has shown antidiabetic property by inducing glucose uptake via increased expression of GLUT-4 and PPAR-γ transcription (Prabhakar & Doble, 2009). The peels and flesh of red and purple potatoes, turnip, Tronchuda cabbage, spinach, etc., are available as vegetable waste or as a byproduct from the processing industries and are rich in phenolic acids (Romani et al. 2006; Ruiz-Rodriguez et al. 2008; Sousa et al. 2008; Tsao, 2009). Hence, these materials may be either employed for the isolation of phenolic acids or fractionated to obtain the crude fraction rich in phenolic acids that may serve as nutraceuticals and preservatives or the entire material might be used as a feed for livestock.

5.3 Extraction of phytobioactives

Extraction is a process that causes the solubility of chemical constituents present in the insoluble solid matrix, leading to mass transfer from the solid matrix into the solvent media employed. Generally, the solid−liquid extraction method is employed for the extraction of various bioactives from plants using different traditional and modern extraction techniques. Solvent extraction methods help in the extraction of anthocyanins, carotenoids, lycopene, flavonoids, tannins, and other polyphenols (Boulekbache-Makhlouf et al., 2013; Kumar et al., 2017; Pimentel-Moral et al., 2020). The commonly used solvents for the extraction of a wide range of phytoconstituents from polar to nonpolar compounds include water, ethanol, methanol, acetone, ethyl acetate, benzene, petroleum ether, etc. (Arora & Itankar, 2018; Mackėla et al., 2017). Among these solvents, ethanol and methanol are the most commonly used for the extraction of important secondary plant metabolites including flavonoids, phenolic acids, etc. (Albuquerque et al., 2018). While conducting extraction of bioactives like carotenoids, precautions must be taken to avoid their degradation due to light, heat, the use of oxidizing agents, and strong acids (Krinsky et al., 2004). In the case of tomatoes, thermal processing has led to an increase in the lycopene content by 12% in tomato juice (Javanmardi & Kubota, 2006). Extraction is carried out by various conventional and modern extraction techniques. The conventional methods of extraction include maceration, infusion, percolation, refluxing, distillation, and Soxhlet extraction techniques (Ćujić et al., 2016). With respect to the conventional extraction techniques, Soxhlet extraction is the most commonly employed solvent extraction method for the extraction of various phytoconstituents including flavonoids (Chávez-González et al., 2020). It is also a simple, cost-effective, and more efficient method that helps in solubilizing many phytoconstituents by using a wide range of extracting solvents compared to other extraction methods like soaking, maceration, and boiling. It is one of the most widely used conventional extraction techniques for the extraction of a wide range of plant bioactives (Sharma & Janmeda, 2017; Pimentel-Moral et al., 2020). Maceration is also one of the most widely used extraction techniques, as it is very simple and does not require any sophisticated instruments. It is used for the extraction of flavonoids, phenolic acids, and other secondary metabolites from plant materials including vegetables like broccoli, cauliflower, Chinese cabbage, white cabbage, etc., and various fruits (Bahorun et al., 2004). Though these extraction methods are simple and cost effective, they require a large amount of solvents and longer duration, and they provide a lower extraction yield. In addition, in certain conventional extraction techniques, heat treatment may cause degradation of plant bioactives, leading to a reduction in the potency of the plant extracts (Farzaneh & Carvalho, 2017). This has led to the existence of modern extraction techniques like ultrasonic extraction, supercritical fluid extraction, accelerated solvent extraction, microwave-assisted extraction, enzyme- assisted extraction, etc.

5.3.1 Ultrasound-assisted extraction

The ultrasound-assisted extraction technique works on the phenomenon of acoustic cavitation that is generated at a frequency of 20 kHz−100 MHz. The formed bubbles rupture near the plant solid matrix, causing the rupture of plant material and resulting in the release of bioactive compounds (Um et al., 2018). The advantages of this method of extraction include that it is faster, with less energy needed, extraction is conducted at room temperature at atmospheric pressure, solvents of all the range can be used, and it provides a moderate yield of extract (Saini et al., 2019). Various flavonoids like rutin, quercetin-3-*O*-rhamnoglucoside, quercetin-3-*O*-glucopyranoside, myricetin, carotenoids like lycopene and beta carotene, catechins, other polyphenols, anthocyanins, saponins, etc. are reported to be extracted using this method (Kumar et al., 2017; Luengo et al., 2014; Pimentel-Moral et al., 2020; Prasad et al., 2009). This is a simple and convenient method of extraction with the ability to extract most of bioactives from the material selected for extraction.

5.3.2 Supercritical fluid extraction

This method of extraction employs supercritical fluid-like carbon dioxide that has properties like high diffusivity, solubility, and low viscosity. These properties help in the extraction of various bioactives with a higher extraction yield in a shorter duration of time. In addition, it is a green extraction technique as the supercritical fluid employed can be recycled, and is nontoxic and cheaper (Kavoura et al., 2019). This method is used for the extraction of flavonoids from spearmint leaves (*Mentha spicata*), lycopene from tomato waste, polyphenols from grape byproducts, catechin, epicatechin, rutin, quercetin, and transresveratrol from the skin of grapes and even in the extraction of various other polyphenols, procyanidins, tocopherols, etc. (Bimakr et al., 2011; Chafer et al., 2005; Kumar et al., 2017; Panja, 2018; Saini et al., 2019). This method of extraction is expensive as it requires a sophisticated instrument that must be operated by a skilled operator. In addition, the chances of degradation of thermosensitive bioactives is greater in this method of extraction.

5.3.3 Accelerated solvent extraction

This method of extraction employs high pressure to penetrate through the solid plant matrix to extract the bioactive compounds. Various phenolic compounds from broccoli, cabbage, and cauliflower (Wu et al., 2004), quercetin from onion skin (Ko et al., 2011) and chlorogenic acid and gallic acid from potato peels (Singh & Saldaña, 2011) were extracted by employing this method of extraction. This is a sophisticated instrument and requires to be operated using skilled labor.

5.3.4 Microwave-assisted extraction

This is a modern extraction technique that employs microwave radiation ranging from 300 MHz (radio radiation) to 300 GHz (infrared radiation) for the extraction of bioactives from plants. This method requires less time, a smaller amount of solvent, and provides a higher extraction yield compared to conventional extraction techniques like maceration, Soxhlet extraction, and reflux extraction. In addition, it can be operated at room temperature at atmospheric pressure (Farzaneh & Carvalho, 2017; Rodríguez-Pérez et al., 2016; Saini et al., 2019). Jha et al. (2017) isolated various flavonoids like quercetin, apigenin, catechin, and phenolic acids like gallic acid, p-coumaric acid, ferulic acid, chlorogenic acid, and syringic acid from black rice using ethanol as solvent. Similarly, Rodríguez-Pérez et al. (2016) isolated flavonoids like quercetin, kaempferol, vitexin, isorhamnetin-3-O-glucoside from *Moringa oleifera* leaves using hydroalcoholic solvent (Rodríguez-Pérez et al., 2016) and lycopene from tomato peel using this extraction technique (Ho et al., 2015).

5.3.5 Enzyme-assisted extraction

EAE is an upcoming and very promising alternative to conventional solvent extraction techniques. Furthermore, the application of enzymes during the extraction is considered as environmentally friendly, as it requires the least amount of organic solvents along with a reduced extraction time and enhanced extraction yield of plant bioactive compounds (Saini et al., 2019). In this method, enzymes derived from various fungi, bacteria, vegetable extracts, and animal organs such as pectinases, glucanases, hemicellulases, and cellulases, either alone or in mixtures are used to break down the cell wall by hydrolysis. This will result in increased permeability of the cell wall to the solvents and increases the yield of bioactives like flavonoids (Castro-Vazquez et al., 2016). This method was used for the extraction of various components, such as carotenoids from pumpkin (Ghosh & Biswas, 2016) and *Capsicum annuum* (Nath et al., 2016), luteolin and apigenin from celery (*Apium graveolens*) leaves using pectinase (Zhang et al., 2011), and also various polyphenols and anthocyanin from grape skin using mixtures of pectinases and cellulases (Maier et al., 2008). In addition, various bioactives like alkaloids, coumarins, flavonoids, phenolic acids, lectins, and terpenoids are also extracted using the EAE technique (Kumar et al., 2017). Enzymatic hydrolysis using pectinase and the ultrasonic-assisted extraction method was employed for the extraction of flavonoids like luteolin and apigenin from pigeon pea (*Cajanus cajan*) leaves (Fu et al., 2008). This method of extraction is not suitable for the extraction of all types of phytobioactives found in vegetable waste as well as their byproducts due to the lack of availability of a wide range of enzymes that can help in releasing all types of bioactives.

5.4 Sustainability through preservation of vegetable waste and byproducts

Vegetable wastes and their byproducts are rich in bioactives of nutritional value, and find their applications in food industries as food additives, nutraceuticals, functional food, etc. Various food and pharmaceutical industries and research institutes need them in huge amounts for various reasons. Thus one of the approaches for sustainability would be to ensure proper coordination between stakeholders and the supply chain system. This will minimize food wastage and the complications associated with the improper disposal of vegetable waste. The vegetable wastes from farmers, as well as the vegetable byproducts derived from the food-processing industries, must be procured. Hence, it must be preserved for a long time to provide these industries with a continuous supply of the phytobioactives. Cultivated vegetables are not only seasonal but also perish rapidly, necessitating the employment of preservation techniques to preserve them before they exceeds their shelf-life (Gil et al., 2015). Various methods are employed for the preservation of vegetable wastes and their byproducts and one of the important methods to extend the shelf-life is drying and preserving them in controlled atmospheric conditions (Mackèla et al., 2017). Drying inhibits the activities of enzymes causing the degradation of bioactives, and also reduces any deterioration due to the action of microorganisms (Rana et al., 2015). Some general methods used for the drying of vegetable byproducts include sun drying, oven drying, and freeze-drying. In the case of apple pomace, the freeze-drying method extends the shelf-life by preserving the bioactives like phenolic compounds and sensory qualities and retains a higher moisture content (Mackėla et al., 2017).

Cooling of vegetables like tubers, stems, green leaves, roots, rhizomes sprouts, bulbs, and their wastes and byproducts, either through room cooling, forced air cooling, vacuum cooling, or package ice packing, will enhance their shelf-life and ensure a sustained supply to the dependent market, industry, and finally consumers. If the nutritional value and its bioactives are unaltered by drying then the vegetable waste or its byproduct is preserved for a long time by drying using appropriate drying technologies. In the case of the storage of colored potatoes and sweet potatoes, there was a significant increase in the amount of anthocyanins when stored at a cold storage of 4°C due to the conversion of starch into sugars, which are considered as the precursors of anthocyanins. Meanwhile, storage of these potatoes at a temperature of 10°C decreased these components. This signifies the influence of storage conditions on the phenolic contents with antioxidant activities (Lachman et al., 2012). If the vegetables and byproducts are made available for the dependent processing industries then this will reduce fluctuations in market supply and price. The preservation technologies also helps in sustainable supply of vegetables and their products round the year (Pollack, 2001). If the vegetables last a long time, all these processes will ensure sustainable production of nutraceuticals, food additives, and phytobioactives.

5.5 Potential applications of vegetable wastes and vegetable byproducts

The bioactives derived from vegetables, their wastes, and industrially processed byproducts have numerous applications. Mainly, the polyphenolic compounds found in them have various health applications in the management/treatment of inflammation, cardiovascular diseases, neurodegenerative diseases, cancer, metabolic diseases, autoimmune diseases, antimicrobial effects, etc. (Table 5.3). Normally, antioxidants are added to fats, oils, and fatty foods in order to inhibit the development of off-flavor induced due to the oxidation of unsaturated fatty acid. In this context, there is a continuous increase in the usage of synthetic antioxidants commercially, but it is strictly controlled due to their associated toxic effects. This has resulted in increased consumer awareness of food additives and their safety, promoting increased interest in the use of natural antioxidants, for example, carotenoids, ascorbic acid, flavonoids, phenolic acids, and tocopherol (Kaur et al., 2011; Rizk et al., 2014). Vegetable byproducts and bioactives find extensive applications in the field of food science, either as food additives (coloring and flavoring agents) or as nutraceuticals, packaging materials, etc. Fifty percent of the population prefers to consume processed food without artificial coloring and preservatives, which necessitates the exploitation of natural additives (Majerska et al., 2019). Beetroot, carrot, red cabbage, and tomato pomace can be utilized as natural pigments and purees in final products such as jam, confectionaries, and beverages. They are rich in natural antioxidants and fiber. Pomace of fruits and vegetables are rich in bioactives compared to their juices obtained from the same fruit and vegetable. Hence, incorporation of these pomace rich in bioactives enriches the food value. A few examples include the utilization of beetroot, carrot, and tomato waste in the production of jams, candies, crackers, and other sweets and snacks. Some can be utilized as a functional food as they are improve health by minimizing the risk of illness.

Dried cassava leaves are processed for the production of feed or food for growing pigs and poultry as they contain a similar proportion of amino acids as soybean meal (Nguyen et al., 2012; Wobeto et al., 2006). Consumption of cassava leaf silage by cattle also increased the production of milk and its fat content (Kavana et al., 2005). Sugar beet pulp obtained as a byproduct from sugar beet refining industries is normally used as a valuable fodder for cattle and other livestock. The pulp is rich in cellulose, hemicelluloses, lignin, and pectin and is highly palatable with a high energy level and is fed either as dried flakes or as compressed pellets. Even the tops of the sugar beet and its crown are employed as forage for ruminant animals (Teimouri Yansari, 2014). The potato byproduct is also a rich source of energy, starch, fiber, and a lower level of protein, and it is utilized as a feed resource for smallholder pig production (Ncobela et al. 2017).

Pomace from various fruits and vegetables consist of peels, skins, and seeds rich in polyphenolic and pectin, hemicelluloses, cellulose, and lignin (Banerjee et al., 2017). The pectin separated from them is made of polygalactouronic acid, which under appropriate conditions can be modified into gels that can be used for the production of edible films that are utilized as a food packaging material. The formulation of pectin with glycerol and starch improves the mechanical and flexible properties of the biofilm (Fishman et al., 2000; Nascimento et al., 2012). Even several vegetable byproducts composed of chitosan are used in the production of nontoxic sustainable edible films (Ferreira et al., 2014). The incorporation of grape pomace extracts to a chitosan film helps in obtaining smooth films with a homogeneous film structure and also enhances the resistance and stiffness. These biopolymers have the advantages of being environmental friendly and low cost, and they also serve as an alternate for synthetic petroleum-based polymers that are nonbiodegradable and impose serious environmental concerns. Cellulose nanofibers are produced using the byproducts of sugar beet, potato tubers, cassava bagasse, etc. by acid hydrolysis or by enzyme treatment (cellulases) which improves the mechanical and barrier properties of the packaging films (Alemdar & Sain, 2008; Azizi Samir, Alloin, Sanchez, El Kissi, & Dufresne, 2004). The vegetable and fruit purees of tomato, carrot, banana, etc. derived from food industries are processed for the production of biofilm and are found to possess good mechanical properties, flavor, water vapor permeability, and oxygen barrier (Du et al., 2008; Wang et al., 2011).

Vegetable byproducts are also used as an alternative source of energy, like biogas and bioethanol (Clemente et al., 2015). The antioxidant potency of the polyphenolic components found in vegetable waste and their byproducts have their application in the cosmetic formulations intended for protection against UV radiation, antiaging creams or lotions, face scrubs, peel-off facials, face masks, face washes, etc. Moreover, various food byproducts rich in anthocyanins as well as tannins are excellent biosorbents as they have the natural ability to adsorb heavy metals, dyes, pharmaceuticals, and surfactants from contaminated water. In addition, they also accumulate various precious and critical metals from the stream of water (Bacelo et al., 2016). Polyphenols like tannins found in tea, quercetin, rutin, and tannins of *Eucalyptus* leaves, as well as anthocyanins found in various flowers and colored vegetables, are also one of the best sources of natural dyes to color silk, cotton, and wool fabrics (Wang et al., 2018). Vegetable waste in the form of pomace of tomato, carrot, beetroot, etc. is employed as a food additive to impart the color or for extrusion. Tomato pomace (2−10 g) is added to barley flour (100 g) to prepare a nutritional snack (Altan et al., 2008). Carrot pomace is also mixed with rice flour (5 g/100 g) to obtain an extruded product (Upadhyay et al., 2010). Cauliflower byproducts are rich in protein and fiber content and upon its incorporation into ready-to-eat snacks it improved the expansion indices, bulk density, and color, and the acceptability was good when the snack was mixed with around 10% cauliflower byproduct (Stojceska et al., 2008).

Vegetable wastes are also employed to prepare biochar, a carbon-rich product obtained when the vegetable waste is heated (at a temperature of 700°C) with little or the absence of oxygen. It contains a huge amount of carbon, hence upon incorporation into soil it leads to an improvement in the soil fertility. In addition, it also enhances the water-holding capacity and as an adsorbent helps in the adsorption of heavy metals. The energy generated during the production of biochar can be utilized as heat or converted into electricity. Sugar beet pulp is heated at 600°C to convert into biochar (Yao et al., 2011). Biogas is renewable energy produced by the decomposition of plants and animal waste, and is mainly composed of methane (45%−70%) and carbon dioxide (30%−45%) with trace amounts of hydrogen, ammonia, and nitrogen (Deressa, Libsu, Chavan, Manaye, & Dabassa, 2015). Fruit and vegetable wastes like potato peelings, green peas, carrots, sugar beet pulp, tomato pomace, asparagus, broccoli, beans, etc. are subjected to anaerobic digestion to generate a significant amount of methane which is used as a biogas in an anaerobic baffled reactor (Bouallagui et al., 2005).

Vegetable waste or byproducts of carrot, tomato, and fennel leaves contain carbohydrates, lipids, proteins, and vitamins that when utilized properly can be served as a medium for bacterial and fungal growth so that they serves as a low-cost medium for the production of cheaper bacterial biomasses. These biomasses will be an ideal source for the production of various enzymes and biopolymers and help in lowering the environmental pollution induced due to the improper disposal of vegetable waste (Di Donato et al., 2011). Various enzymes, organic acids, flavoring agents, natural colorants, bioethanol, biomethanol, etc. are derived from vegetable and fruit wastes by microbial application (Laufenberg et al., 2003). In various cases, vegetable and fruit wastes are used for the production of organic acids like lactic acid and citric acid using microbes such as *Aspergillus* species (Panda et al., 2016; Ray et al., 2008), for the production of enzymes like cellulase, amylase, and protease employing *Bacillus* species (Oyeleke et al., 2011; Pothiraj et al., 2006), for the production of feed using *Saccharomyces cerevisiae* (Correia et al. 2007), and for the production of bafilomycin, oxytetracyclin, and cephamycin using *Streptomyces* species (Mussatto et al. 2012).

Vegetable wastes are rich in organic content, with abundant availability and high biodegradability and could be utilized as a substrate for a bioelectrochemical system to convert their chemical energy into electrical energy through a cascade of redox reactions with the help of microbial fuel cells. Thus this process ensures the dual benefit of the generation of renewable energy in the form of bioelectricity and remediation of vegetable waste. This is mainly due to the presence of a significant amount of organic components in food wastes and agro-residues (ElMekawy et al., 2015). The anaerobic digestion of molasses and its byproducts, with the help of microorganisms, produces methane and carbon dioxide that can be used as a fuel for the generation of electricity (Polematidis, Koppar, & Pullammanappallil, 2010). Vegetable wastes through a bioelectrochemical system generated a power output of 57 mW/m^2 and upon the prefermentation of vegetable waste the power output was doubled to 111 mW/m^2 (Venkata Mohan et al., 2010).

5.6 Conclusion, opportunities, and future challenges

A host of vegetables and fruits are commercially cultivated primarily for consumption as well as for the production of processed foods worldwide. However, due to on-farm and/or off-farm factors, around 30% of these vegetables and fruits are wasted. In addition, food-processing industries also contribute to the generation of a considerable amount of vegetable byproducts. The vegetable waste generated globally is rich in carbohydrates, proteins, fats, phenolic compounds, natural colorants, etc. However, the amount of vegetable waste is very significant, attracting concerns over environmental pollution due to their improper disposal and treatment, and researchers from around the globe are conducting studies to transform this waste into value-added products. In order to minimize the generation of waste, a zero-waste strategy can be implemented which includes the utilization of vegetable byproducts as an ideal source of food additives like coloring, flavoring, preservatives, etc., in the preparation of snacks, juice, and bakery goods to replace synthetic chemicals, as functional foods and nutraceuticals. Vegetable wastes are employed in the production of animal feed that will be available at low cost and in turn will solve the problem associated with improper disposal of food-processing industries. This will ensure both environmental and financial sustainability.

Vegetable waste serves as a cost-effective substrate for the production of various commercially important enzymes and organic acids of industrial applications through microbial processing. Regulating the prices of horticultural crops by government agencies attracts farmers to cultivate these vegetables, ensuring the continuous supply of vegetables to society and food-processing industries. Through various preservation technologies, vegetables, their wastes, and byproducts must be preserved by extending their shelf-life for a sustained supply to the dependent industries. Preservation technologies also ensure functioning of the dependent vegetable market and food-processing industries, and avoid fluctuations in the price due to the lack of supply of the same. Another strategy could be exploring vegetable wastes and byproducts as a good source of phytobioactives that hold significant importance in pharmaceutical industries and herbal drug industries. This will ultimately avoid the overexploitation of medicinal crops, as well as losses incurred by farmers due to vegetable waste. Vegetable waste is also converted into biochars and used as bioadsorbents for wastewater treatment. Most of the research conducted into the utilization of vegetable waste is restricted to the laboratory scale, and only a few pilot scales and very few studies have been commercialized to scaling up processes so far. This necessitates multidisciplinary approaches to transform the studies related to vegetable waste valorization from the laboratory scale to the industrial scale.

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