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Fruit and Vegetable Waste: Bioactive Compounds, Their Extraction, and Possible Utilization

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Abstract: Fruits and vegetables are the most utilized commodities among all horticultural crops. They are consumed raw, minimally processed, as well as processed, due to their nutrients and health-promoting compounds. With the growing population and changing diet habits, the production and processing of horticultural crops, especially fruits and vegetables, have increased very significantly to fulfill the increasing demands. Significant losses and waste in the fresh and processing industries are becoming a serious nutritional, economical, and environmental problem. For example, the United Nations Food and Agriculture Organization (FAO) has estimated that losses and waste in fruits and vegetables are the highest among all types of foods, and may reach up to 60%. The processing operations of fruits and vegetables produce significant wastes of by-products, which constitute about 25% to 30% of a whole commodity group. The waste is composed mainly of seed, skin, rind, and pomace, containing good sources of potentially valuable bioactive compounds, such as carotenoids, polyphenols, dietary fibers, vitamins, enzymes, and oils, among others. These phytochemicals can be utilized in different industries including the food industry, for the development of functional or enriched foods, the health industry for medicines and pharmaceuticals, and the textile industry, among others. The use of waste for the production of various crucial bioactive components is an important step toward sustainable development. This review describes the types and nature of the waste that originates from fruits and vegetables, the bioactive components in the waste, their extraction techniques, and the potential utilization of the obtained bioactive compounds.

Keywords: bioactive compounds, by-products, horticulture, phytochemicals, postharvest, processing

Introduction

Fruits and vegetables have a crucial role in our diet and human life, and therefore the demand for such important food commodities has increased very significantly as a result of the growing world population and the changing dietary habits (Schieber and others 2001; Vilariño and others 2017). Examples of the significant amount of fruits produced globally include 124.73 million metric tons (MMT) of citrus, 114.08 MMT of bananas, 84.63 MMT of apples, 74.49 MMT of grapes, 45.22 MMT of mangoes, mangosteens, and guavas, and 25.43 MMT of pineapples (FAO 2017). Production of some vegetables include potato (3820.00 MMT), tomatoes (171.00 MMT), cabbages and other brassicas (71.77 MMT), carrots and turnips (38.83 MMT), cauliflower and broccoli (24.17 MMT), and peas (17.42 MMT) (FAO 2017).

Higher production and growth, and the lack of proper handling methods and infrastructure, have led to huge losses and waste of these important food commodities, as well as their components and by-products and residues. For example, the United Nations Food and Agriculture Organization (FAO) has estimated that at least one-third of the food produced in the world (estimated as 1.3 billion metric tons) is lost and wasted every year (FAO 2014), and losses and waste of horticultural commodities are the highest among all types of foods, reaching up to 60% (Gustavsson and others 2011). Losses and waste occur during all phases of the supply and handling chain, including during harvesting, transport to packinghouses or markets, classification and grading, storage, marketing, processing, and at home before or after preparation. Losses occur throughout the supply chain from production throughout all postharvest stages before consumption. They are the unintended result of the way food production and supply systems function in their institutional and legal framework (Parfitt and others 2010). Waste, on the other hand, is food that is fit for consumption, but is not consumed and instead discarded, and this generally relates to consumer or retailer behavior (FAO 2014). Although losses and waste can be considered distinct, and each has its own causes and solutions, they are nonetheless interrelated and sometimes difficult to distinguish, and therefore they will be referred together or in conjunction throughout this paper. Losses and waste can be assessed quantitatively and qualitatively (FAO 2014). Quantitatively they refer to masses or volumes, which reduce the amount of food available for consumption. Qualitatively, they represent decreases in edibility, nutrition, caloric value, consumer acceptability,

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economic value, which all are recognized before the food item is discarded. Qualitative losses and waste are very difficult to assess and quantify, despite their important impact on nutrition, health, and economic returns. Losses and waste of horticultural commodities are high in developing as well as in developed countries, but at different points of the handling chain. It is common that losses are higher in so-called developing countries due to lack of proper handling techniques, while waste is higher in developed countries and affluent societies in developing countries. In other words, food losses are commonly the result of technical limitations in infrastructure and handling, such as storage, packing, packaging, marketing, while food waste is commonly the result of negligence or a conscious decision to through food away. Kader (2005) estimated that approximately one-third of all fruits and vegetables produced worldwide are lost during postharvest (excluding losses before harvest and waste after reaching the consumer) and do not reach the consumer. Waste after reaching the consumer is also very significant, especially in developed countries. Postharvest losses in the United States are estimated to be 2% to 23% depending on the commodity, with an overall average of 12% (Kader 2005). A tentative estimate of postharvest losses from the United Kingdom is suggested to be 9%, not including produce left in the field because it fails to meet acceptability and other quality criteria (Garnett 2006). Buzby and others (2011) also estimated that the total value of fruit and vegetable losses at the retail and consumer levels in the United States was $42.8 billion in 2008 or roughly $141 per person. FAO (2014) revealed that processing, packaging, distribution, and consumption of fruits and vegetables in the developed parts of China, India, Philippines, and the United States alone produce approximately 55 MMT of fruit and vegetable waste (FVW). Kummu and others (2012) noted that global agricultural losses could be reduced by 47% and global consumption waste by 86% pointing out that the global potential improvement is largest in regions where there is the lowest need for extra food supply.

The food processing industries have seen rapid growth throughout the world during the last few decades, but also major losses and waste during processing. For example, food and drink waste in the United Kingdom is estimated to be approximately 14 MMT, of which 20% is associated with food processing, distribution, and retail (Parfitt and others 2010).

Fruit and vegetable losses and waste do not represent only the wasting of food commodities, but also indirectly include wasting of critical resources such as land, water, fertilizers, chemicals, energy, and labor. These immense quantities of lost and wasted food commodities also contribute to immense environmental problems as they decompose in landfills and emit harmful greenhouse gases (Venkat 2011; Vilariño and others 2017). Followed by household garbage, fruit and vegetable processing units commonly produce the highest wastes into the environment (Gowe 2015).

The horticultural waste is a rich source of potentially valuable bioactive compounds. Unfortunately, horticulture by-products have not been taken very seriously in the past as very valuable materials, but the scenario has been changing lately, since FVWs are could be used to recover highly valuable biomolecules. Horticultural by-products are excellent sources of pigments, phenolic compounds, dietary fibers, sugar derivatives, organic acids, and minerals, among other components (Figure 1). Several of these bioactive compounds possess beneficial health attributes: antibacterial, antitumor, antiviral, antimutagenic, and cardioprotective activities (Dilas and others 2009; Yahia 2010, 2017). Many fruits and vegetables, such as oranges, pineapples, peaches, apples, potatoes, carrots, green peas, onions, artichokes, and asparagus, are utilized for juice or pulp extraction, jams, and frozen pulp, producing significant amounts of waste (Rodriguez and others 1999, 2006).

The WSDE (1994) report revealed that reduction of waste increases profit, reduces liability, lowers water use and waste, and also creates good public relations. FVWs can be used to extract and isolate potential bioactive compounds that can be used in the food, pharmaceutical, cosmetics, and textile industries. Therefore, although some of the waste can be considered unavoidable one, the proper use of waste materials acquired from horticultural commodities may establish an initiative for sustainable development to mitigate environmental problems and to improve human health through foods enriched with health-enhancing substances (phenols, carotenoids, and other pigments, vitamins, dietary fibers, among several others). This review explores fruit and vegetable losses and waste as natural resources of bioactive compounds, and their extraction methods and potential uses are also discussed.

Nature and Extent of Fruit and Vegetable Losses and Waste

Losses and waste are the unused or unconsumed parts of a fruit, a vegetable, and other food stuff, as a result of morphological characteristics of the commodity, lack of proper handling operations, or simply discarded for diverse reasons. Besides this, by-products of horticultural commodities discarded after processing constitute a significant waste. However, quantity and type of FVWs vary from commodity to commodity and morphological components, including leaves, roots, tubers, skin, pulp, seeds, stones, pomace, and so on (Panouillé and others 2007). Many fruits and vegetables generate at least up to 25% to 30% of waste materials, which are not further used (Ajila and others 2007, 2010). Laufenberg and others (2009) have estimated the production and total waste of fruits and vegetables during processing (Figure 2).

Many fruits and vegetables are not consumed raw and therefore are first processed to obtain the required product (Ayala-Zavala and others 2010). Coffee and macadamia are some examples that generate by-products with very rich biomolecules (Miljkovic and Bignami 2002). As far as the wastage is concerned, apples generate 10.91% of seed and pulp as by-products, and 89.09% of final products during slicing. Dicing of papaya produces about 8.5% of peel waste, 6.5% of seeds, 32% unsuable pulp (because of imperfection in cubes), and about 53% of final product. The peeling of mandarins generates about 16% of peels and 84% of finished product. Pineapple processing yields about 14% of peels, 9% of core, 15% of pulp, 15% of top, and 48% of total final product. Processing of mangoes produces about 11% of peels, 13.5% of seeds, 18% of inoperable pulp, and 58% of finished product (Ayala-Zavala and others 2010; Joshi and others 2012). Moreover, juice production from fruits and vegetables produces around 5.5 MMT of waste including pomace. Grape and wine processing industries generate around 5 to 9 MMT of solid waste yearly worldwide, which constitutes 20% to 30% of processed materials (Schieber and others 2001). Canning and frozen industries of fruits and vegetables generate approximately 6 MMT of solid waste annually, which is composed of 20% to 30% leaves, stalks, and stems (Panouillé and others 2007). The nature of fruit and vegetable losses and waste is illustrated in Table 1.

Bioactive Compounds from Fruit and Vegetable Losses and Waste

FVW are rich sources of phytochemicals and have been studied for the extraction of phenolic compounds, dietary fibers, and

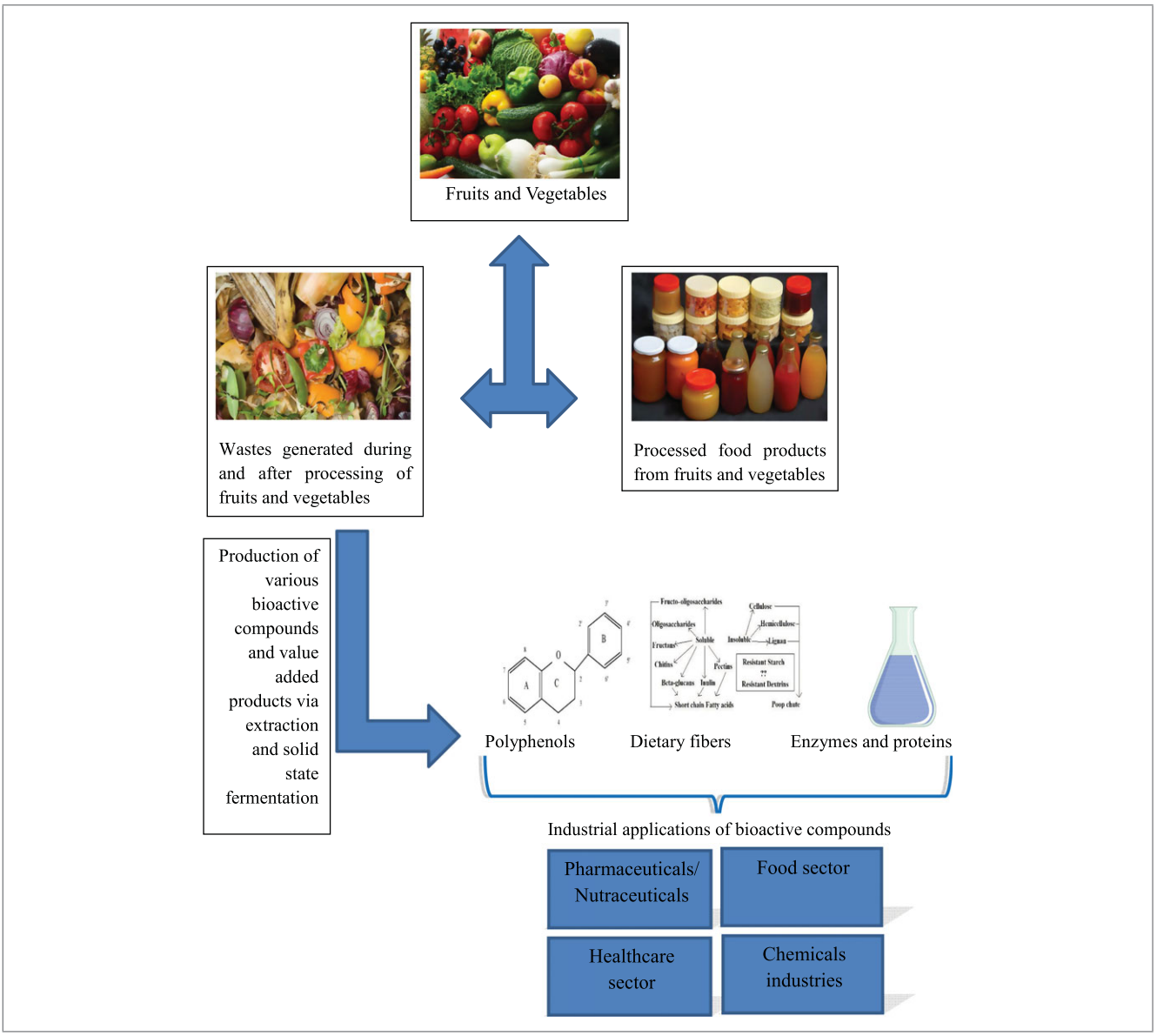

Figure 1–Graphical illustration of the fate of fruit and vegetable wastes.
***These estimates are for wasted (not lost) commodities, as defined in the "Introduction" section.**

other bioactive compounds (Galanakis 2012). In most fruits and vegetables, only the flesh or pulp is consumed, but studies have revealed that significant amounts of phytochemicals and essential nutrients are present in the seeds, peels, and other components of fruits and vegetables not commonly consumed (Rudra and others 2015). For example, the peels of lemons, grapes, and oranges, and the seeds of avocados, jackfruits, longans, and mangoes contain more than 15% higher phenolic concentrations than that found in the fruit pulp (Gorinstein and others 2001a; Soong and Barlow 2004). It is important to point out that FVW are prone to microbial spoilage causing objectionable odors and environmental problems. In general, wastes should be processed using thermal (heating, microwave, radiofrequency, infrared heating, and sterilization) or nonthermal (high hydrostatic pressure, ultrasound, pulsed electric fields (PEFs), irradiation, and pulsed light) technologies, which may affect phytochemicals. The following are some of the bioactive components that can be counted as examples of important biomolecules that can be obtained from FVW.

Dietary fibers

Dietary fiber concentrations in vegetable waste. Dietary fibers are found in all layers of the onion but in different ratios. Jaime and others (2002) investigated the entire onion from skin to the inner layers of 3 different varieties for dietary fiber contents. They found the highest amount of total dietary fibers (TDFs) in the skin (68.3% dry matter [DM]) of the "Grano de Oro" onion, and the lowest (11.6% DM) in the inner part. Insoluble fibers were also reported to be higher (66.6% DM) in the skin of the onion "Grano de Oro" compared to the inner part. Benitez and others (2013) stabilized triturated onion waste (paste) and triturated + pressed onion waste ("bagasse," solid residue and "juice," liquid fraction) by pasteurization and sterilization. They observed that industrial processing had an important impact on the bioactive composition, generating products with different functional applications. Moreover, pasteurization was the most suitable treatment to obtain safe products enriched with dietary fiber and fructans, while sterilization caused products rich in alkenyl cystein sulfoxide (ACSO).

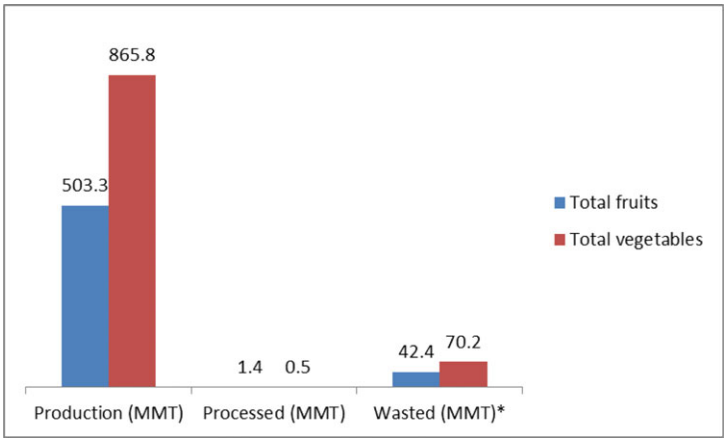

Figure 2–Global production of fruits and vegetables, processed and wasted quantities (million metric tons, MMT). Modified from Laufenberg and others (2009).

Table 1–Nature of potential fruit and vegetable losses and waste.

Commodity	Nature of waste	Typical losses and waste (%)	References
Apple	Pomace, peel, and seeds	–	Gupta and Joshi (2000)
Banana	Peel	35	Gupta and Joshi (2000)
Citrus	Rag, peel, and seeds	50	Gupta and Joshi (2000)
Dragon fruit	Rind, seeds	30 to 45	Cheok and others (2018)
Durian	Skin, seeds	60 to 70	Siriphanich and Yahia (2011)
Grapes	Skin, stem, and seeds	20	Gupta and Joshi (2000)
Guava	Peel, core, and seeds	10	Gupta and Joshi (2000)
Jackfruit	Rind, seeds	50 to 70	Saxena and others (2011)
Mango	Peel, stone	45	Gupta and Joshi (2000), Mitra and others (2013)
Mangosteen	Skin, seeds	60 to 75	Chen and others (2011), Ketsa and others (2011)
Onion	Outer leaves	–	Gupta and Joshi (2000)
Papaya	Rind, seeds	10 to 20	Lee and others (2011), Parni and Verma (2014)
Passion fruit	Skin, seeds	45 to 50	Arjona and others (1991), Esquivel and others (2007), Almeida and others (2015)
Peas	Shell	40	Gupta and Joshi (2000)
Pineapple	Core, skin	33	Ketnawa and others (2011), Choonut and others (2014)
Potato	Peel	15	Gupta and Joshi (2000)
Rambutan	Skin, seeds	50 to 65	Sirisompong and others (2011), Issara and others (2014)
Tomato	Core, skin, and seeds	20	Gupta and Joshi (2000)

–: Data not available.

The results indicated that bagasse was an enriched dietary fiber product (361 to 453 mg/g DM); paste showed high alkyl (ACSO) content (5.6 mg/g DM); and juice showed large fructan concentrations (205 to 221 mg/g DM). In paste and bagasse, pasteurization and sterilization improved soluble/insoluble fiber ratios, with no changes in (TDF) concentration in pasteurized products and a slight decrease (8% on average) in the sterilized ones. In juice, thermal treatments produced fructan losses, more pronounced after sterilization (59% on average) than after pasteurization (36% on average). However, sterilization provided by-products with better ACSO results than pasteurization.

Three varieties of potato and their peels were investigated and no significant differences were found in the total fiber concentrations. Five Polish potato varieties (Hermes, Saturna, Rosalind, Raja, and Courage) had 9.51, 9.94, 9.73, 10.30, and 9.35 g/100 g DM, respectively (Gumul and others 2011). According to Ncobela and others (2017), potato peel contains 61.0 to 125 g/kg crude fiber in the DM. Potato solid waste was also reported as a good source of fiber (27 to 35 g/100 g) (Afifi 2011; Sharoba and others 2013). Potato pulp is rich in dietary fibers (especially in rhamnogalacturonan I) and is an underutilized material produced in large quantities by potato starch factories (Byg and others 2012). Thed and Phillips (1995) analyzed the cooking impact on the TDF contents in potato, and found significant increments from 7.60% DM (control) to 8.92% DM by deep-fat frying and 9.08% DM by microwave-heating. Peeled potatoes also contained 72.4% DM of total starch (Liu and others 2007).

By-products (stems and florets) from cauliflower were analyzed for nonstarch polysaccharides (NSPs), and stems contained higher amounts (3.11% fresh weight, FW) than florets (2.31% FW). In both types of waste, insoluble fibers were higher than soluble fibers. Pectic polysaccharides were the main component of NSP (Femenia and others 1997, 1998). Florkiewicz and others (2014) evaluated the effect of different technological processing methods (blanching, cooking, and freezing) on the contents of DM, protein, fat, ash, mineral compounds, as well as dietary fiber in white floret cauliflower and cauliflower with conical, green–yellow florets. Processing method significantly influences the contents of nutrients and dietary fibers, and it is a major factor determining the extent of nutrient losses. The cooking of raw cauliflower results in lower losses of nutrients than cooking of frozen cauliflower.

Carrot pomace was analyzed for dietary fiber content, and it was found to be 63.6% DM. Of this, insoluble fibers were 50.10% DM and soluble fibers were 13.50% DM (Chau and others 2004). Fresh carrot peels were also studied for dietary fiber contents and the effect of blanching on them. The peel content of TDFs significantly increased from 45.45% DM to 73.32% DM after blanching (Chantaro and others 2008).

On a dry weight basis, tomato pomace contains up to 50% fibers (Del Valle and others 2006). Herrera and others (2010) formed tomato fiber with the fusion of ground and dried tomato peel. They investigated tomato fiber for TDF content, reporting 82.7% FW, and the ratio of insoluble to soluble fibers was 10:1. Fresh tomato matter wasted by the agroindustry can be preserved for 140 d through silage (Mendez-Llorente and others 2014). Tadeu Pontes and others (1996) obtained a 2-fold increase in soluble dietary fiber, 108.6% when extruding tomato pomace in association with a starch component, corn semula, using a single-screw extruder. Wang and others (2013) used ultrasonic-assisted extraction enhacing the yield of dietary fiber from corn pericarp.

Dietary fiber concentrations in fruit waste. Apple peel had higher dietary fiber content (0.91% FW) than the pulp. The percentage of insoluble and soluble dietary fibers was 0.46% FW and 0.43% FW, respectively (Gorinstein and others 2001b). Apple pomace is a waste material from apple juice processing and contains significant amounts of dietary fiber. Yan and Kerr (2013) observed that TDF ranged from 442 to 495 g/kg in vacuum-dried pomace and was not significantly different from the freeze-dried pomace (480 g/kg). Ultrasound-assisted extraction provided higher soluble dietary fiber yield in apple pomace than when microwave or acid hydrolysis techniques were used (Li and others 2014).

Grapes pomace was found to be a rich source of dietary fibers, namely, hemicelluloses, cellulose, and small proportions of pectins (Kammerer and others 2005). González-Centeno and others (2010) investigated the by-products (stems, pomace) of 10 varieties of grapes. The red grape cultivar "Tempranillo" had the highest dietary fiber content in the pomace (36.90 g/100 g FW), stem (34.80 g/100 g FW), and fruit (5.10 g/100 g FW). "Manto Negro" red grape pomace TDF content was 77.20% DM, and soluble fibers were lower (3.77% DM) than the insoluble fibers (73.50% DM) (Llobera and Cañellas 2007). The TDFs of red grape pomace was the same as that of the white grape pomace (71.56% DM, in "Prensal Blanc" cultivar). Among the TDFs, the soluble fraction (10.33% DM) was found again to be less than the insoluble fraction (61.26% DM) in the white grape pomace (Llobera and Cañellas 2008). Deng and others (2011) conducted a study using dried grape pomace skin and found that the red pomace samples contained between 51% and 56% TDF, whereas the white grape pomace contained only approximately half of the percentage of red grape pomace TDF (17% to 28%). Although there were significant differences between the red and white pomaces, both had insoluble dietary fiber percentages above 97% (insoluble dietary fiber/TDF).

Mango by-products have been shown to possess high amounts of dietary fibers. Mango peel contains 51.2% DM of TDFs (32% DM insoluble fibers and 19% DM soluble fibers) (Ajila and others 2007, 2008). Ajila and Prasada Rao (2013) analyzed dietary fiber of mango peels and found that the TDF content was in the range of 40.6% to 72.5%, with galactose, glucose, and arabinose being the major neutral sugars in insoluble and soluble dietary fibers. "Tommy Atkins" mango had 28.05% DM of dietary fibers, including 13.80% DM insoluble and 14.25% DM soluble fibers (Vergara-Valencia and others 2007). The kernel has 2% crude fiber (Elegbede and others 1995; Nzikou and others 2010). Dhingra and Kapoor (1985) found 1.75% of crude fiber in mango seed kernel. Changso (2008) also analyzed mango seed kernel and found it to have 3.96% of crude fiber. Moreover, Ashoush and Gadallah (2011) found 0.26 ± 0.07 (mean ± SD) g/100 g crude fiber in mango kernel powder and 9.33 ± 0.61 (mean ± SD) g/100 g crude fiber in mango peel powder.

The peel of "Liucheng" oranges was reported to contain 57% DW TDFs, of which 9.41% DW was the soluble fraction and 47.6% DW the insoluble fraction, and the main components of the fibers were characterized as cellulose and pectin polysaccharides (Chau and Huang 2003). Dietary fibers in lemon peels were 14 g/100 g DM, which is much higher than for peeled lemon (7.34 g/100 g DM) (Gorinstein and others 2001a). Of the TDFs, insoluble and soluble fibers were 9.04 g/100 g DM and 4.93 g/100 g DM, respectively. Lemon peel and pulp contain good amounts of soluble and insoluble dietary fiber. In particular, dietary fiber amount was higher in the pulp, with a total of 77.93%, while the peel had 53.02%. The amount of the soluble fraction was 27.91% and 18.48% in pulp and peels, respectively. It has been reported that soluble fraction ranging between 34.5% and 35.8% of the TDF in the peel and pulp, respectively, is optimal for human consumption (Russo and others 2014).

Dietary fibers in peach (cv. Sudanell) were reported to be 30.7% to 36.1% DM, and constituted 12.3% DM soluble fibers and 23.8% DM insoluble fibers (Chang and others 2000). Kurz and others (2008) investigated the polysaccharides in the cell wall of peach fruit and found pectin as the main polysaccharide. Small differences were reported between unpeeled and peeled peaches with regard to hemicellulose, lignin, and cellulose. Peeled peaches contained 17.0 g/100 g alcohol-insoluble residue (AIR) cellulose and 13.1 g/100 g AIR hemicellulose, whereas unpeeled peaches contained 16.4 g/100 g AIR and 12.9 g/100 g AIR, respectively (Kurz and others 2008). The TDF concentrations in the waste of different fruits and vegetables are summarized in Table 2.

Phenolic compounds

Phenolic compounds are the plant secondary metabolites responsible sensory characteristics and contribute to the nutritional quality of fruits and vegetables (Tomás-Barberán and others 2000; Lapornik and others 2005), among other functions. Phenolic compounds are among the largest classes of bioactive compounds with diverse and important biological functions (Popa and others 2008; Ignat and others 2011). They contain 1 or more aromatic rings along with 1 or more hydroxyl groups in their basic structure (Balasundram and others 2006), and some have antioxidant activity (Heim and others 2002). Polyphenolic compounds are classified into various classes such as flavonoids (subclasses: flavonols, flavanones, flavones, flavanonols, isoflavones, flavanols, and anthocyanidins), tannnis, stilbenes, phenolic acids, and lignans (Hollman and Katan 1999; Robbins 2003), among other classes.

The rind, peel, and seeds of fruits and vegetables possess high amounts of phenolic compounds. In the case of vegetable wastes, potato peel was reported as a good source of phenolic compounds as it possesses 50% of phenolics out of the whole bioactive components content (Friedman 1997). Choi and others (2016) investigated the "Superior" variety of Korean potato and found the peel to have a higher amount (385 ± 50 μg/g DW chlorogenic acid, 21.9 ± 2.0 μg/g DW chlorogenic acid isomer II, and 103 ± 10 μg/g DW caffeic acid) of phenols than the cortex (107 ± 4 μg/g DW chlorogenic acid, 4.2 ± 1.2 μg/g DW chlorogenic

Table 2–Total (TDF), insoluble (IDF), and soluble (SDF) dietary fiber contents in the waste of different fruits and vegetables.

Commodity	Type of waste	TDF (%)	IDF (%)	SDF (%)	References
Apple	Peel	0.91	0.46	0.43	Gorinstein and others (2001b)
Apple	Pomace	88.5	69.9	18.6	Renard and Thibault (1991)
Apricot	Seeds	27 to 35	–	–	Seker and others (2010)
Banana	Peel	50 (IDF:SDF ratio 5.46:1)	–	–	Wachirasiri and others (2009)
Carrot	Pomace	63.6	50.1	13.5	Chau and others (2004)
Cauliflower	Stem	3.11	–	–	Femenia and others (1997, 2002)
Cranberry	Seeds	51.06	45.93	5.13	CSF (2013)
Dates	Seeds	57.87 to 92.4	–	–	Almana and Mahmoud (1994), Al-Farsi and Lee (2008), Elleuch and others (2008)
Garlic	Husk	62.23	58.07	4.16	Kallel and others (2014)
Grapes	Seeds	40	–	–	Bagchi and others (2002)
Grapes	Pomace	77.9	68.4	9.5	Valiente and others (1995)
Grapes	Pomace	77.2	73.5	3.77	Llobera and Cañellas (2007)
Green chilli	Peel and seeds	80.41	–	–	Matsuda (1997), Mckee and Latner (2000)
Kiwifruit	Pomace	25.80	18.70	7.10	Martin-Cabrejas and others (1995)
Lemon	Peel	14	9.04	4.93	Gorinstein and others (2001a)
Mango	Peel	51.2	32	19	Ajila and others (2007, 2008)
Onion	Skin	68.3	–	–	Jaime and others (2002)
Orange	Peel	57	47.6	9.41	Chau and Huang (2003)
Pea	Hulls	91.5	87.4	4.1	Ralet and others (1993)
Peach	Pomace	54.5	35.5	19.1	Pagan and Ibarz (1999)
Pear	Pomace	43.9	36.3	7.6	Martin-Cabrejas and others (1995)
Potato	Peel	5.6	–	–	Liu and others (2007)
Pumpkin	Pomace	76.94	–	–	Turksoy and Özkaya (2011)
Raspberry	Pomace	77.5	75	2.5	Gorecka and others (2010)
Tomato	Pomace	50	25	25	Del Valle and others (2006)

–: Data not available.

acid isomer II, and 2.29 ± 0.51 μg/g DW caffeic acid) of the same. Cucumber peel was reported as a cheap source of flavonoids for industrial purposes (Agarwal and others 2012). According to a study by Zeyada and others (2008), FVWs were found to be rich in phenolic content in the following increasing order: olive leaves > tomato peel > cucumber peel > watermelon peel > potato peel.

Date seeds are excellent source of phenolic compounds and antioxidants (Al-Farsi and Lee 2008). The oil extracted from the seeds has higher phenolic content than most edible oils except the olives (Besbes and others 2005). The seed extracts of 5 vegetables (*Cucumis sativus*, *Cucurbita pepo*, *Momordica charantia*, *Lagenaria siceraria,* and *Praecitrullus fistulosus*) have been found to be highly effective against several microbes, including *Escherichia coli, Fusarium oxysporium, Streptococcus thermophilus, Serratia marcescens,* and *Trichoderma reesei* (Sood and others 2012; Sonia and others 2016), which might be due, at least in part, to their high content of phenolic compounds.

The citrus industry produces major amounts of seeds and peel residues, which constitute about 50% of the total fruit (Bocco and others 1998; Ignat and others 2011). Citrus waste is a rich source of phenolic compounds because citrus peel contains a higher quantity of polyphenols in comparison with the edible part of the fruit (Balasundram and others 2006). Apart from citrus, the peels of other fruits have also been found to contain higher concentrations of phenolics compared with the edible portions. For example, Gorinstein and others (2001b) found double amounts of total phenolics in the peels of apples, peaches, and pears compared to peeled fruits. It was reported that banana pulp (*Musa cavendish*) contains 232 mg/100 g DM of phenolic compounds, which is only about 25% of that found in the peel (Someya and others 2002). Along with phenolic compounds, higher amounts of catecholamines, dopamine, and L-dopa were also found in banana peels (González-Montelongo and others 2010). Pomegranate peels contain 249.4 mg/g phenolic compounds, while the pulp contains 24.4 mg/g (Li and others 2006a). The peels of 8 selected cultivars of Clingstone peaches were reported to contain more than 2.0 to 2.5 times higher concentration of phenolic compounds than the edible flesh (Chang and others 2000). Apple peels were reported to have up to 3300 mg/100 g DM of phenolic content (Wolfe and Liu 2003). Grape skins and seeds, by-products of the juice and wine industries, are also rich sources of mono-, oligo-, and polymeric proanthocyanidins (phenolics) (Shrikhande 2000; Torres and Bobet 2001). Extraction of phenolic compounds depends on the technique used, and therefore, it is possible to increase their extraction from kinnow (*Citrus reticulate* L.) peel waste by 4 times using the ultrasound-assisted extraction than the maceration technique (Safdar and others 2016). The types of polyphenols in the waste of different fruits and vegetables are reported in Table 3.

Flavoring agents and aromas

The waste materials of fruits and vegetables are an important source of various bioproducts that can serve as a source of flavors and aromas. Solid state fermentation (SSF) is a conversion technique by which many potential products have been isolated from FVWs, including flavors, ethanol, enzymes, methane, citric acid, lactic acid, and various food ingredients (Zheng and Shetty 1998). An overview of such flavors, aromas, enzymes, and organic acids is given in Table 4.

The market for aromas, fragrances, and flavors has increased because of increased consumer demand for natural, familiar, and safe sources. Vanillin (4-hydroxy-3-methoxybenzaldehyde) is produced from vanillic acid. Vanillin is the main component of vanilla flavor, which is the most important and highly used flavor in the food, cosmetic, pharmaceutical, and detergent industries (Tilay and others 2008). The extraction of natural vanillin is achieved from the fermented pods of vanilla orchids (*Vanilla planifolia*) (Panouillé and others 2007). The production of vanillin has also been reported using alternative methods including biotechnology, which include fermentation and enzymatic reactions, such as an enzymatic method to produce vanillin from capsaicin and red pepper, among others. Pineapple peel waste contains ferulic acid, a precursor for vanillic acid. An increase in demand for natural flavors has triggered research on natural vanillin production from natural raw materials through microbial

Table 3–Phenolic compounds present in some fruit and vegetable wastes.

Commodity	Waste part	Phenolic compounds	References
		Fruits	
Apple	Pomace	Hydroxycinnamates, phloretin glycosides, quercetin glycosides, catechins, procyanidins	Lu and Foo (1998), Foo and Lu (1999), Lommen and others (2000), Schieber and others (2001)
Apple	Leaves	Quercetin-3-*O*-galactoside, quercetin-3-*O*-rhamnoside, (+) catechin, procyanidin B1, (−) epicatechin, phloretin-2′xylo-glucoside, phloridzin, chlorogenic acid, cryptochlorogenic acid	Teleszko and Wojdyło (2015)
Banana	Bract	Cyanidin, anthocyanidins (delphinidin, pelargonidin, peonidin, petunidin, malvidin)	Pazmino-Durán and others (2001)
Banana	Peel	Carotenoids (palmitate or caprate, xanthophylls, laurate)	Subagio and others (1996)
Bilberry	Leaves	Caffeic acid, myricetin-3-*O*-galactoside	Teleszko and Wojdyło (2015)
Chokeberry	Leaves	(−) epicatechin, neochlorogenic acid, chlorogenic acid, quercetin-3-*O*-rutinoside, quercetin-3-*O*-robinobioside, quercetin-3-*O*-galactoside	Teleszko and Wojdyło (2015)
Citrus fruits	Peel and solid residues	Eriocitrin, hesperidin, naringin	Coll and others (1998), Matharu and others (2016)
Cranberry	Leaves	(+) Catechin, procyanidin B1, (−) epicatechin, myricetin-3-xylopiranoside, quercetin-3-*O*-galactoside, dimethoxymyricetin-hexoside, methoxyquercetin-pentoside	Teleszko and Wojdyło (2015)
Grapes	Seeds	Procyanidins	Kallithraka and others (1995), Fuleki and Ricardo da Silva (1997), Saito and others (1998), Jayaprakasha and others (2001)
Grapes	Pomace	Catechins, anthocyanins, stilbenes, flavonol glycosides	Schieber and others (2001)
Grapes	Skin	Catechin, epicatechin, epigallocatechin, picatechin gallate	Souquet and others (1996)
Kiwifruit	Peel	Caffeic acid, protocatechuic acid, p-coumaric acid	Mattila and others (2006), Wijngaard and others (2009)
Mango	Seed kernel	Gallates, gallotannins, gallic acid, ellagic acid	Arogba (2000), Schieber and others (2001)
Mango	Peel	Flavonol glycosides	Schieber and others (2000)
Purple star apple	Peel	Ferulic, sinapic caffeic, gallic, myricetin, ellagic	Moo-Huchin and others (2015)
Quince	Leaves	(+) Catechin, procyanidin B1, procyanidin B2, procyanidin C1, 4-*O*-caffeoylquinic acid, kaempferol-3-*O*-rutinoside, kaempferol-3-*O*-glucoside, quercetin-3-*O*-galactoside, quercetin-3-*O*-rutinoside	Benzarti and others (2015), Teleszko and Wojdyło (2015)
Red cashew	Peel	Myricetin, ferulic, sinapic caffeic, gallic, ellagic	Moo-Huchin and others (2015), Visioli and others (1998, 1999)
Olive	Oil waste water	Oleuropein and hydroxytyrosol derivatives	
		Vegetables	
Carrot	Pomace	Carotene (α and β)	Schieber and others (2001)
Garlic	Husk	Di-ferulic acid, hydroxybenzoic acid, p-coumaric acid, caffeic acid-*O*-glucoside, coumaric acid-*O*-glucoside, caffeoylputrescine	Kallel and others (2014)
Onion	Skin	Quercetin 3,40-*O*-diglucoside and quercetin 40-*O*-monoglucoside	Price and Rhodes (1997)
Potato	Peel	Chlorogenic, gallic, protocatechuic and caffeic acids, chlorogenic acid isomer II	Onyeneho and Hettiarachchy (1993), Rodriguez and others (1994), Choi and others (2016)
Red beet	Peel	ltryptophane, p-coumaric and ferulic acids, cyclodopa glucoside derivatives	Kujala and others (2001)
Tomato	Skin	Lycopene	Sharma and Le Maguer (1996)

biotransformation (Priefert and others 2001). Vanillin synthesis from pineapple waste is a 3-step process (Lun and others 2014).

Apart from vanillin, other aromas are also obtained from plant by-products. At the commercial level, rhamnose is obtained through chemical hydrolysis from rutin or citrus fruits. L-Rhamnose is the main component of cell wall pectins, and it is the raw material used for the production of the strawberry flavor "furaneol" (2,5-dimethyl-4-hydroxy-3(2H)-furanone) (Haleva-Toledo and others 1999). The pineapple flavor component "ethyl butyrate" is produced with the help of a microorganism, *Ceratocystis fimbriata*, from apple pomace. The coconut flavor component "δ-decalactone" is also produced through a bioconversion method with the help of *Ceratocystis moniliformis* from olive press cake (Lanza and others 1976). Volatile compounds from pineapple processing residues (rind and fibers left behind after the juice extraction step) were extracted and 35 volatile compounds were identified. The principal compounds identified were esters (37%), alcohols (29%), aldehydes (9%), ketones (9%), and acids (6%) (Barreto and others 2013). This property indicates that they have potential for the production of aromatic natural essences, which could later be added to products such as pineapple juice concentrate to enhance its sensory quality (Dorta and Sogi 2017).

Enzymes

Amylases (EC 3.2.1.1). This group is composed of 3 enzymes, namely α-amylase, β-amylase, and glucoamylase. Both SSF and submerged fermentation (SMF) have been employed for amylase production, but traditionally SMF is the preferred choice for the production of commercially important amylases because many environmental factors, such as temperature and pH, can be easily controlled and handled (Gangadharan and others 2008). Many fruit residues (Table 4) are used as substrate for the production of amylases. Some examples include banana waste (Krishna and Chandrasekaran 1996; Unakal and others 2012), date waste

Table 4–Overview of flavor, enzymes and organic acids produced from fruit and vegetable waste using microorganisms.

Product	Waste/substrate	Microorganism used	References
		Flavors	
Pineapple (ethyl butyrate)	Apple pomace	*Ceratocystis fimbriata*	Laufenberg and others (2003)
Banana (isoamyl acetate)	Carrot pomace	*Ceratocystis fimbriata*	Fischbach and others (2000)
Vanillin	Carrot pomace	*Pycnoporus cinnabarius*	Asther and others (1996), Bonnin and others (1999), Laufenberg and others (2003)
Vanillin	Sugar beet pulp	*Aspergillus niger*	Lesage-Meessen and others (1999), Laufenberg and others (2003)
δ-Decalactone (coconut), γ-decalactone	Olive press cake	*Ceratocystis moniliformis, Pityrosporum ovale*	Lanza and others (1976), Laufenberg and others (2001)
		Enzymes	
Amylases	Banana waste	*Bacillus subtilis*	Unakal and others (2012)
	Cabbage waste	*Pseudomonas* sp.	Kunamneni and others (2005)
	Cassava waste	*Bacillus sp.*	Selvama and others (2016)
	Coconut oil cake	*Aspergillus oryzae*	Rosales and others (2005)
	Date waste	*Aspergillus niger*	Said and others (2014)
	Loquat kernels	*Penicillium expansum*	Erdal and Taskin (2010)
	Mango kernel	*Fusarium solani*	Kumar and others (2013)
	Orange waste	*Streptomyces sp.*	Mahmoud (2015)
	Potato peel	*Bacillus subtilis*	Mushtaq and others (2017)
Cellulases	Banana solid waste	*Cellulomonas carte, Bacillus megaterium, Penicillium putida, Pseudomonas fluorescence*	Dabhi and others (2014)
	Banana waste	*Bacillus* sp.	Sukumaran and others (2005)
	Cabbage waste	*Pseudomonas* sp.	Kunamneni and others (2005)
	Kinnow waste	*Trichoderma reesei*	Oberoi and others (2010)
	Mango peel	*Aspergillus niger*	Bakir and others (2001)
	Palm kernel cake and vegetable waste	*Bacillus* sp	Norsalwani and Norulaini (2012)
Invertases	Peels of orange, pineapple, pomegranate, sapota	*Aspergillus flavus*	Uma and others (2010)
	Banana peel, pineapple peel	*Aspergillus niger*	Mehta and Duhan (2014)
Laccases	Apple, grape seeds, kiwifruit waste, orange peel, potato peelings	*Trametes hirsute*	Rosales and others (2002, 2007), Couto and others (2006), Botella and others (2007)
	Orange waste	*Pleurotus* sp.	Inacio and others (2015)
Laccases, xylanases	Banana waste	*Aspergillus* spp. MPS-002, *Phylostica* spp. MPS-001	Krishna and Chandrasekaran (1995)
	Banana skin	*Trametes pubescens*	Osma and others (2007)
Lipases	Lemon peel	*Chaloropsis thielarioides, Colletotrichum gloesporioides*	Parihar (2012)
	Coconut cake	*Aspergillus niger*	Venkatesagowda and others (2015)
	Mahua cake	*Lasiodiplodia theobromae*	Kumar and Kanwar (2012)
Pectinases	Apple, strawberry pomace	*Lentinus edodes*	Shah and others (2005)
	Pineapple peel	*Penicillium chrysogenum*	Okafor and others (2010)
	Banana peel, lemon peel, orange peel, and waste	*Bacillus* sp., *Aspergillus niger, Penicillium citrinum*	Bayoumi and others (2008), Mrudula and Anitharaj (2011), Sandhya and Kurup (2013)
	Waste of banana, cashew apple, grape, pineapple	*Aspergillus foetidus*	Venkatesh and others (2009)
Pectinases, cellulases, xylanases	Grape pomace	*Aspergillus awamori*	Botella and others (2005)
Tannases	Tamarind seed powder	*Aspergillus niger* ATCC 16620	Pandey and others (2000)
	Jamun (*Syzygium cumini*) leaves	*Aspergillus ruber*	Kumar and others (2007)
Xylanases	Apple, pomace, hazelnut, shell, melon peel, palm kernel cake, tamarind seed	*Trichoderma harzianum* 1073 D3	Sabu and others (2005), Seyis and Aksoz (2005)
	Orange peel	*Aspergillus niger*	Mamma and others (2008)
	Pineapple peel powder	*Trichoderma koeningi*	Bandikari and others 2014
	Watermelon rind, melon peels	*Trichoderma* sp.	Isil and Nilufer (2005), Mohamed and others (2013)
	Tomato waste	*Aspergillus awamori*	Umsza-Guez and others (2011)
α-Amylases	Citrus peel	Not mentioned	Mohamed and others (2010)
		Organic acids	
Acetic acid	Papaya peel, Pineapple peel	*Acetobacter aceti* + *Saccharomyces cerevisiae*	Raji and others (2012), Vikas and Mridul (2014)
Citric acid	Cassava bagasse, coffee husk, moasmi peel, pineapple peel	*Aspergillus niger*	Vandenberghe and others (2000), Kumar and others (2003), Prabha and Rangaiah (2014)
	Apple pomace	*Aspergillus niger, Yarrowia lipolytica*	Shojaosadati and Babaeipour (2002), Dhillon and others (2011)
Lactic acid	Cassava bagasse	*Lactobacillus delbrueckii*	John and others (2006)
	Cassava fibrous residue, green peas, mango peel, orange peel, potato peel, sweet corn,	*Lactobacillus casei, L. plantarum, L. delbrueckii*	Ray and others (2008), Mudaliyar and others (2012), Jawad and others (2013), Krishnakumar (2013), Panda and Ray (2015)

(Said and others 2014), citrus waste (Mohamed and others 2010; Mahmoud 2015), potato peels (Mushtaq and others 2017), cassava waste (Selvama and others 2016), loquat kernels (Erdal and Taskin 2010), and mango kernels (Kumar and others 2013). Moreover, Djekrif-Dakhmouche and others (2006) utilized orange waste powder to produce α-amylase with the help of *Aspergillus niger* ATCC16404.

Amylases are produced by a variety of microorganisms such as *A. niger*, *Aspergillus awamori*, *Aspergillus oryzae*, *Aspergillus tamarii*, *Bacillus subtilis*, *Bacillus licheniformis*, *Rhizopus oryzae*, *Candida guilliermondii,* and *Thermomyces lanuginosus*. Among these, *A. niger*, *B. subtilis* and *R. oryzae* are the most applied species in the industry (Said and others 2014).

Amylases are widely used in the food processing industries for various products: fruit juices, starch syrup, moist cakes, chocolate cakes, and so on, and different processes such as brewing, preparation of digestive aids, and baking (Laufenberg and others 2009).

Cellulases (EC 3.2.1.4). Cellulases consist of exo-1,4-β-glucanase, endo-1,4-β-D-glucanase, and β-D-glucosidase. They are used in the food industries, in the liberation of aroma-rich compounds, as well as in the extraction of phenolic compounds (Table 4) from grapes pomace, among others (Drider and others 1994; Meyer and others 1998). Palm kernel cake and vegetable waste were used as substrates to produce cellulases by *Bacillus* spp. through SSF (Norsalwani and Norulaini 2012). Kinnow waste was also used to produce endo-1,4-β-glucanase (CMCase) and filter-paperase (FPase) with the help of *Trichoderma reesei* and wheat bran in the ratio of 3:2 and 4:1, respectively (Oberoi and others 2010). When a bacterial mixture of *Cellulomonas carte, Bacillus megaterium, Pseudomonas putida,* and *Pseudomonas fluorescence* was mixed with banana solid waste, it showed an increased quantity of cellulase (FPase: 0.178 U/mL on the 20th day) and β,D-glucosidase (0.602 U/mL on the 25th day) (Dabhi and others 2014). Potato peel was found to be a good carbon source for *A. niger* to produce cellulytic enzymes (dos Santos and others 2012). Reddy and others (2003) investigated banana waste as a substrate for *A. niger, Pleurotus sajorcaju,* and *Pleurotus ostreatus* for the production of cellulolytic and lignolytic enzymes, and reported that leaf biomass was best suited as substrate for the production of enzyme, compared to pseudostems.

Invertase (EC 3.2.1.26). Invertase is used to produce invert sugar. Invertase possesses a low crystallinity level compared to sucrose, and therefore, it keeps the product soft and fresh for a longer period of time (Kumar and Kesavapillai 2012). Uma and others (2010) optimized the conditions (30 °C, 4 d incubation time, 3% inoculum size, pH 5) for the production of invertase by *Aspergillus flavus*. A higher level of invertase production was reported under optimized conditions using fruit peel waste as the substrate. Likewise, *A. niger* was mixed with various carbon sources such as fructose, fruit peel, lactose, and sucrose to produce invertase. Among them, fructose was found to be the best carbon source for the production of extracellular invertase. When a fruit peel combination (1 sapota, 2 pineapples, 2 bananas) was used as a substrate, invertase was produced in lower activity, compared to fructose as the main carbon source. However, the invertase production with fruit peels as the source of carbon had higher activity than the lactose case (Mehta and Duhan 2014). Invertase is specifically used to produce candies, jam, and confectionary, and pharmaceutical products (Panda and others 2016).

Pectinases (such as *EC* 3.2.1.15, polygalacturonase). Pectinases degrade pectic compounds, which are important fruit and vegetable structural components in cell walls. Pectate lyase and pectin lyase can sort the long carbon chain by breaking its glycosidic bonds, while pectin esterase works on methoxyl groups. The production of pectinase is done by SSF from grape pomace using *A. awamori* yeast (Botella and others 2005). Okafor and others (2010) used different FVW as the source of carbon for the pectinolytic molds, *Penicilliim chrysogenum* and *A. niger. P. chrysogenum* produced high amounts of pectinase (220.3 IU/mg protein) with the peel of pineapple. Mrudula and Anitharaj (2011) used 6 different substrates (lemon peel, orange peel, banana peel, wheat bran, rice bran, and sugarcane bagasse) for pectinase production using *A. niger* in SSF. Orange peel showed the best result among all substrates for the production of pectinase (1224 U/g DMS). Apart from this, another fungus, *Aspergillus foetidus*, was used for the production of pectinase utilizing tropical fruit wastes in 5-g amounts (grape, pineapple, banana, and cashew apple) along with 0.25 g of $(NH_4)_2SO_4$ + 0.05 g of urea. The medium with grape waste showed the best result at 40 °C with 8 d of incubation (Venkatesh and others 2009). Pectin enzymes have various important applications in the food industries (fruit juices and wines) for extraction, clarification, and concentration. Moreover, the extraction of flavors, pigments, and essential oils are achieved using these enzymes from plant residues (Castilho and others 2000).

Other enzymes. Tannases (*EC* 3.1.1.20, tannin-acyl-hydrolase), xylanases (*EC* 3.2.1.8), laccases (*EC* 1.10.3.2), and proteases (*EC* 3.4.21.19) are some other enzymes that are also produced by SSF techniques (Rodríguez Couto 2008). These enzymes are also extensively used in the food industries for important product formations. For example, tannase is applied to clarify fruit juices and beer, to manufacture dyes, gallic acid, and instant tea (Ramirez-Coronel and others 2003; Banerjee and others 2005). Tamarind seed powder and palm kernel cake were used for the production of tannase by *A. niger.* The tannase yield was 13.03 IU/g ds (units per gram of dry substrate) and 6.44 IU/g ds for palm kernel cake and tamarind seed powder, respectively (Sabu and others 2005). Kumar and others (2007) utilized tannin-rich waste like jamun leaves (*Syzygium cumini*), amla leaves (*Phyllanthus emblica*), ber leaves (*Ziziphus mauritiana*), and others for tannase production using *Aspergillus ruber*; and highest titer of tannase (69 U/g ds) was found with jamun leaves. Likewise, extracellular tannase was produced using ber, amla, and jamun leaves by *Penicillium atramentosum* under SMF. Among them, amla (2% w/v) produced the highest quantity (32.8 U/mL) of tannase (Selwal and Selwal 2012). Varadharajan and others (2016) analyzed different horticultural wastes to produce tannase under SMF by *A. oryzae.* They concluded that pomegranate rind extract yielded 138.12 IU/mL tannase. Xylanase is used to extract starch and plant oils. It is applied to produce food thickeners and to create different textures in baked products (Krishna 2005). Laccase applications included the detoxification of industrial effluents, mostly from the paper and pulp, textile and petrochemical industries, as bioremediation agent to clean up herbicides, pesticides, and certain explosives in soil, as cleaning agents for certain water purification systems, as catalysts for the manufacture of anticancer drugs, and even as ingredients in cosmetics. In addition, their capacity to remove xenobiotic substances and produce polymeric products makes them a useful tool for bioremediation purposes (Rodríguez Couto and Toca Herrera 2006). After the 3rd day of incubation, tomato pomace had the highest laccase titer (362 U/L fermentation broth) when it was mixed with *Coriolus versicolor* as the carbon source for the production of laccase (do Rosario Freixo and others 2008). Besides this, laccase enzyme has also been retrieved from the seed shell of apricots by *Trametes trogii (Berk.)* ATCC 200800 and by *Trametes versicolor* (L.)

ATCC 200801 under SMF and semisolid state (Birhanli and others 2013). Proteases remain the dominant enzymes because of their extensive use in the detergent and dairy industries (Kirk and others 2002). Various agroindustrial wastes have been extensively investigated for protease production along with vegetables and fruit wastes (Bharathiraja and others 2017). Sandhya and others (2005) produced neutral protease by utilizing palm kernel cake, coconut oil cake, jackfruit seed powder, and olive oil cake as substrates for *A. oryzae* in addition to agrowaste. In another study, alkaline protease was produced using chickpea waste along with different agroindustrial wastes by *Bacillus* spp (Prakasham and others 2006).

Organic acids

Organic acids are important biomolecules used in the food, cosmetic, and chemical industries. Citric and lactic acids are the most important for the food and pharmaceutical sectors. Citric acid can be produced by fermentation using various molds, yeasts, and bacteria. However, *A. niger* remains as a favorite mold species for the industrial production of citric acid (Swain and others 2011). Coffee husk and cassava bagasse were used to produce citric acid using *A. niger* by the SSF process. Cassava bagasse is an excellent substrate to achieve high citric acid content (Vandenberghe and others 2000). Apple pomace has also been used as substrate material with *A. niger* to produce up to 80% of citric acid (Shojaosadati and Babaeipour 2002; Dhillon and others 2011) as well as the waste of pineapple, mandarins, and mixed fruits yielding 51.4%, 50%, and 46.5% of citric acid, respectively (Kumar and others 2003; Prabha and Rangaiah 2014). Imandi and others (2008) also produced a maximum amount of citric acid from pineapple waste by using the yeast *Yarrowia lipolytica*, and by pineapple and its waste using *A. niger* as the acting fermenter.

Lactic acid has an important place in the carboxylic acids group because it has various applications in the food as well as the nonfood industries. In food products, it is basically used as acidulant and preservative (Rodríguez Couto 2008). The main problem in the production of lactic acid is the cost of raw material. John and others (2006) found that under optimized conditions, the total sugars of cassava bagasse can be converted into 99% of lactic acid by *Lactobacillus delbrueckii* using the SSF technique. Lactic acid can be produced by various microorganisms using by-products of fruits and vegetables. *Lactobacillus casei, Lactobacillus delbrueckii,* and *Lactobacillus plantarum* have been used to produce lactic acid using potato peel, sweet corn, mango, orange, green peas, and cassava residue as the substrates (Ray and others 2008; Mudaliyar and others 2012; Jawad and others 2013; Panda and Ray 2015).

Proteins

Proteins are the most crucial biomolecules to form body muscles, and they are also the necessary component of various other body molecules. Protein deficiency may lead to many adverse conditions and diseases. The nonedible portions and waste of several fruits and vegetables have been reported as good sources of proteins. According to Choi and others (2016), Korean "Superior" potato peel was a good source of protein (10.6 ± 0.2 g/100 g DW and 1.80 ± 0.03 g/100 g in FW). Chitturi and others (2013) analyzed the peels of various fruits using the Lowry method for protein analysis and found high amount of protein in the peels of kiwifruit, avocado, and papaya fruit (1.79%, 1.57%, and 1.55%, respectively). Citrus peels had 2.5% to 9.0% protein content (Dugo and Di Giacomo 2002; Pfaltzgraff and others 2013; Mamma and Christakopoulos 2014). In the proteome profiling of citrus fruit, 1109 proteins were reported among which 366 were found in the peel and 46 in the peel and pulp (Fasoli and Righetti 2015; Lerma-García and others 2016). Besides this, other FVW were also analyzed and found to have good amount of proteins, such as carrot pomace (10.06 g), apple pomace (4.45 g), mosambi peel (5.4 g), green pea peels (13.27 g), mango peel (9.5 g), pineapple peel (8.7 g), banana peel (6.02 g), orange peel (5.97 g), potato solid waste (3 to 5 g), tomato solid waste (17 to 22 g), cabbage leaves (20.4 g), cauliflower leaves (16.1 g), and pea pods, peel, and shell (20.2 g) per 100 g (Sharma and others 2016). Moreover, some other FVW were also utilized to isolate different protein molecules such as actinidin from the seeds of kiwifruit (Boland 2013), leptin from jackfruit seeds (Devalaraja and others 2011), and vicilin-like protein from the seeds of watermelons (Wani and others 2008).

Extraction of Bioactive Compounds

Extraction is the most critical step to obtain bioactive compounds from FVW (Khoddami and others 2013). Ideal methods of extraction determine proper types and quantities of bioactive compounds that can be obtained from FVW (Smith 2003; Sasidharan and others 2011; Baiano 2014). Extraction methods may vary with respect to the targeted bioactive compounds. Bioactive components can be characterized after identification from stem, flower, leaves, and fruits. Many factors such as temperature, plant part, pressure, and type of solvent may affect the extraction process (Hernández and others 2009). Sample preparation is also one of the crucial factors to determine the type and amount of bioactive compounds extracted. For example, Dorta and others (2012a) applied 3 different combinations of dehydration methods (freeze drying, oven drying with static air at 70 °C, and oven drying with forced air at 70 °C with ethanol, ethanol:water, and acetone:water as solvents) on mango peel and seed for the extraction of bioactive compounds. Results revealed that extraction of freeze-dried mango peel and seed with ethanol:water contained the highest amount of phenolics and anthocyanins.

The bioactive compounds of plant waste can be extracted with different methods, which can be classified into 2 main categories: conventional and novel techniques. The comparative advantages and limitations of various extraction techniques are summarized in Table 5.

Conventional extraction techniques

The classical methods are considered as conventional techniques because they have been used for a long time. The base of these techniques is basically the solvent extraction power and the applied heat or their combination. Main conventional techniques include (1) Soxhlet extraction, (2) hydro-distillation and (3) maceration (Khoddami and others 2013). Soxhlet extraction has been very popular and widely used as the classical technique to extract useful bioactive components from different plant parts, but initially it was developed only for lipid extraction. The 1st Soxhlet extractor was designed by German scientist French Ritter von Soxhlet (Soxhlet 1879). New extraction techniques are compared with this old method because it is the basic model technique for new techniques. Basically, a very small dry sample amount is kept in a thimble, then the thimble is kept in the distillation flask that contains the solvent of choice. When it reaches an overflow level, a siphon aspirates the solution from the thimble-holder and returns it back into the distillation flask. This solution contains and carries the extract into the bulk liquid. The solute of extract stays in the distillation flask and the solvent moves back to the solid plant

Table 5–Comparative advantages and limitations of various extraction methods for bioactive compounds.

Technique	Advantages	Limitations	Recommended compounds	References
Soxhlet	• Widely used as classical technique • Basic model technique for the comparison of other techniques	• Time consuming • Not environmentally friendly and requires large quantities of solvents	Lipid/fat extraction	Soxhlet (1879), Garcia-Salas and others (2010), Azmir and others (2013)
Hydro-distillation	• Oldest and simplest technique for extracting essential oils from plants • Best suited for small-scale industries • Provides different options according to choice, that is, hydro-distillation, steam and water distillation, direct steam distillation, hydro-diffusion, and so on.	• Not suitable for heat-labile compounds because they may be lost or degraded at high temperature • Time-consuming and slow process	Oil and bioactive compounds	Vankar (2004), Azmir and others (2013)
Liquid–liquid extraction (LLE)	• Suitable for liquid samples • Standard, easy, and cheap method for determining phenol in water • Can be utilized at room temperature to avoid phenolics degradation	• Requires hazardous and expensive chemicals • Labor intensive • Requires long time for sample analysis and degradation rate is high due to internal and external factors	Best for phenolic compounds, liquid by-products from beverage industries are best samples for this technique	Espinosa-Alonso and others (2006), Garcia-Salas and others (2010)
Solid-phase extraction	• Separation rate is faster than LLE • Easy to use with little manual efforts • High repeatability than LLE	• Expensive than LLE • Specifically for more polar compounds • Unsuitable for volatile analytes because of evaporative losses	Best suited for phytochemicals in medicinal plants	Hernanz and others (2008), Garcia-Salas and others (2010), Vuckovic (2013), Abd-Talib and others (2014)
Supercritical fluid extraction (SFE)	• Lower viscosity and higher diffusion coefficient than liquid solvent extraction, which gives better mass transfer • Time saving and environment friendly due to requirement of little amount of sample and organic solvent • Minimum wastage because reusing and recycling of supercritical fluid is possible • Suitable for volatile compounds because performed at room temperature	• Not suitable for most drug and pharmaceutical samples • Polar molecules cannot be dissolved • Costly system thermodynamics complicated	Best suited for volatile compounds	Mendiola and others (2007), Abbas and others (2008)
Pressurized liquid extraction (PLE)	• Suited for solid samples to isolate biomolecules • Better for polar compounds instead of supercritical fluid extraction • Less time consuming and less solvent required	• Higher equipment cost • Unsuitable for samples with very low level of targeted analytes because 10 g is the maximum limit of sample weight	Agro-industrial by-products for phytochemical extraction	Kaufmann and Christen (2002), Suchan and others (2004), Klejdus and others (2009), Dobiáš and others (2010)
Pulsed electric field (PEF)	• Can be applied in continuous mode up to 10000 kg/h • Short extraction time and improved extraction yield • Facilitation of purified extract (reducing, grinding) • Reduced environmental impact compared to the conventional extraction, reduced energy cost	• Process parameters, energy inputs, treatment temperature, field strength are required to maintain	Best for phytosterols and various polyphenols	Heinz and others (2003), Puértolas and others (2012), Barba and others (2015)
Enzyme-assisted extraction (EAE)	• Eco-friendly because it uses water as solvent in place of organic chemicals • Significantly suitable to extract bound compounds • High extraction rate	• High enzyme cost for large volumes of samples • Not feasible at industrial level due to the behavior of enzymes • Moisture content of the sample, particle size, hydrolysis time, enzyme concentration, and composition are the key factors to be maintained carefully	For the extraction of oil and bounded phytochemicals	Dominguez and others (1995), Rosenthal and others (1996), Singh and others (1999), Niranjan and Hanmoungjai (2004), Puri and others (2012)

(Continued)

Table 5–Continued.

Technique	Advantages	Limitations	Recommended compounds	References
Microwave-assisted extraction (MAE)	• Better quality and high selectivity of desired extracts • High extraction yield and less extraction time • Cost-effective compared with solvent extraction technique • Simply operable and economically feasible in comparison with supercritical fluid extraction • Short extraction time compared with ultrasonic-assisted extraction	• Apparatus and equipment are expensive • Operation is difficult compared to ultrasonic-assisted extraction • Less environment friendly due use of organic solvents • Poor extraction yield for nonpolar compounds • Unfit for heat-labile biomolecules	For the rapid extraction of bioactive compounds (especially polyphenols)	Huie (2002), Kaufmann and Christen (2002), Wang and Weller (2006), Chen and others (2007), Cravotto and others (2008), Sticher (2008), Zhang and others (2009, 2011)
Ultrasound-assisted extraction (UAE)	• Less energy and power usage • Higher product yield • Short processing time and less chemical usage	• Proper optimization in ultrasound frequency, nominal power of the device, propagation of cycle, input power, system geometry is required for maximum yield	Phenolic compounds, lipids, chlorophyll, carotenoids	Azmir and others (2013), Barba and others (2015)
High-voltage electrical discharge (HVED)	• Low energy required for the extraction of biomolecules in comparison with other emerging technologies (PEF, UAE, MAE, and so on.) • Less time and solvent use • Low diffusion temperature required	• Less selective compared with PEF • Feasibility at industrial or pilot level is unknown	Polyphenols	Barba and others (2015)

material again and again. The process runs continuously until the extraction is achieved.

Hydro-distillation is also a classical technique to extract important oils and various bioactive compounds from plant sources, and it is used before dehydrating a plant sample. There are 3 kinds of hydro-distillation: water and steam distillation, water distillation, and direct steam distillation (Vankar 2004). The starting step of a hydro-distillation is the packing of the plant sample in a still compartment. Then, a sufficient amount of water is added and boiled. Steam can also be used as the alternative. Hot water and steam work as the effective removal agents for the bioactive compounds from the plant cells. The vapor mixture of oil and water is condensed by indirect water cooling. The condensed mixture moves to a separator from the condenser. Here the bioactive compounds and oil split automatically from the water (Silva and others 2005). Hydro-distillation includes 3 significant physicochemical processes named hydro-diffusion, hydrolysis, and decomposition by heat. It is not good for heat-labile compounds because they may be lost or degraded at the high extraction temperature.

Maceration has been used for a long time for the preparation of tonics at home. It became popular as a low-cost technique to obtain bioactive compounds and essential oils. It is highly suitable for low extractions and is composed of several steps. First is the complete grinding of plant samples into tiny particles for the proper mixing with solvent. In the 2nd step, an appropriate quantity of the solvent, called menstruum, is poured into a closed vessel. Then, in the 3rd step, the liquid is discarded and a large amount of the prepared solution is achieved by pressing the solid residue of this extraction process. Finally, filtration is used to separate the pressed liquid to remove impurities. Sometimes, shaking during maceration is used to increase the extraction in 2 ways: (1) to increase diffusion and (2) to discard concentrated solution from the sample surface and add new solvent to the menstruum for maximum extraction yield.

Novel technologies

The novel techniques emerge because of the limitations of the conventional methods. Conventional methods of extraction are characterized with difficulty to obtain high purity, use of costly solvents, longer time of extraction, possible degradation of heat-labile compounds, and low extraction selectivity (De Castro and Garcia-Ayuso 1998). To deal with these limitations, novel techniques have been developed. There are several novel and emerging techniques that are being utilized now for the extraction process. The main novel and emerging techniques are described below.

Microwave-assisted extraction. Microwave-assisted extraction (MAE) is also known as a novel technique for the extraction of various phytochemicals utilizing microwave vitality (Paré and others 1994). The electromagnetic field of microwaves ranges from 300 MHz to 300 GHz. They are composed of 2 perpendicular fields: magnetic field and electric field. The heating principle utilizing microwaves is based upon its immediate effects on polar materials (Letellier and Budzinski 1999). Microwave energy is transformed into heat through dipole rotation and ionic conduction mechanisms (Jain and others 2009). Heat is produced due to the resistance of medium during the ionic flow or conduction whereas the other side-ions align themselves toward the direction of field and change randomly. This change in the direction creates collision among molecules and heat is generated. The MAE technique is composed of 3 subsequent steps (Alupului and others 2012). The 1st step is splitting and separation of solute molecules from the sample matrix because of increased pressure and temperature. The 2nd step involves solvent diffusion alongside the sample matrix. The 3rd step is solutes release into solvent from the sample.

Many benefits of MAE have been described, including decreased equipment size, high extract amount and temperature gradient, and transient heating to extract bioactive components from plant materials (Cravotto and others 2008).

MAE can extract the bioactive compounds rapidly and efficiently as compared to conventional technologies. It is considered as a "green" technique, since it reduces the use of organic solvents (Alupului and others 2012). The extraction yield of caffeine and polyphenols using MAE from the leaves of green tea was higher at 4 min than any other methods of extraction (Pan and others 2003). The extraction for ginsenosides from ginseng root was achieved in 15 min by the MAE technique and it was much better compared to conventional solvent extractions for 10 h (Shu and others 2003). Dorta and others (2013a) compared MAE and traditional solvent extraction (TE) for antioxidant extractions from mango peel. They found that MAE was better than TE, and they reported 1.5 to 6.0 times more phytochemical and antioxidant power in the extract achieved by MAE. For the antioxidants from mango seed, Dorta and others (2013b) optimized the factors affecting the antioxidant extraction. They achieved higher contents of antioxidants using acetone/water (50:50 v/v) as the extraction solvent mix, 1:30 (w/v) seed weight to solvent volume ratio, and without using the microwave and a pH of 8.0. The optimization of MAE operation from Chinese quince (*Chaenomeles sinensis*) was carried out for extraction time, solvent concentration, and microwave power using preplanned experiments for maximum recovery of phenolic compounds, particularly flavonoids, and also to increase the electron-donating quality of the extracts (Teng and others 2009).

Pulsed electric field. The PEF technique has been reported as beneficial to improve the process of drying, extraction, diffusion, and pressing (Barsotti and others 1998; Angersbach and others 2000; Vorobiev and others 2005; Vorobiev and Lebovka 2006). The principle of PEF is to increase the extraction by breaking the structure of cell membranes. Electric charge splits the molecules of the cell membranes on the basis of charges due to their dipole nature. When the critical value of transmembrane potential reaches 1 V, the repulsion arises between charged molecules, which increases the pores at the weak sides of membranes and causes permeability (Bryant and Wolfe 1987). Generally, a simple circuit is used for plant samples with exponential decay to apply PEF treatment. It is composed of a treatment chamber, which contains 2 electrodes and where a plant sample is placed. The PEF method can be applied in a continuous or a batch mode, it depends upon the design of treatment chamber (Puértolas and others 2010). Specific energy input, treatment temperature, electric field strength, and material properties are the parameters on which the effectiveness of the PEF process is based (Heinz and others 2003). An optimum electric field (500 and 1000 V/cm) prevents temperature increase, which has little impact on plant cell membranes (Fincan and Dejmek 2002; Lebovka and others 2002). For this reason, PEF minimizes the degradation of heat-labile compounds (Ade-Omowaye and others 2001).

When PEF was applied for the extraction of phytosterols from maize and isoflavonoids (daidzein and genistein) from soybeans, recovery was increased by 32.4% for maize and 21% for soybean (Guderjan and others 2005). PEF was found to be the best among various techniques when bioactive compounds (anthocyanin monoglucosides) were extracted from grape by-products (Corrales and others 2008). PEF treatment on "Merlot" grape skin resulted in high amounts of anthocyanins and polyphenols (Delsart and others 2012).

Enzyme-assisted extraction. Enzymatic pretreatment has also been recognized as a novel and useful way to retrieve bound compounds and increase their yield (Rosenthal and others 1996). There are basically 2 ways for enzyme-assisted extraction (EAE), one is enzyme-assisted cold pressing (EACP) and the 2nd is enzyme-assisted aqueous extraction (EAAE) (Latif and Anwar 2009). Basically, EAAE techniques have been developed fundamentally for the extraction of oils from different seeds (Hanmoungjai and others 2001; Sharma and others 2002). Different elements including catalyst type, molecular size of plant materials, water proportion, and the hydrolysis time are perceived as key factors for extraction (Niranjan and Hanmoungjai 2004). Phosphorus and free fatty acid contents were found comparatively higher in oil extracted by EAE rather than traditionally extracted oil (Dominguez and others 1995). EAE is considered as an eco-friendly method to extract oils and bioactive compounds because water is used as the solvent in place of organic solvents (Puri and others 2012).

The antioxidants in grape pomace were analyzed during wine production and a correlation was found between breakdown degree of cell wall by enzymes and total phenolic yield (Meyer and others 1998). Landbo and Meyer (2001) reported higher amounts in the pomace of *Ribes nigrum* using various enzymes. The total phenolic compounds in the peel of 5 citrus fruits ("Meyer" lemon, mandarin, "Yen Ben" lemon, grapefruit, and orange) were highest when achieved with celluzyme MX among different enzymes (Li and others 2006b). Gómez-García and others (2012) reported the best effect of novoferm enzyme among the pectinex, celluclast, and novoferm enzyme group during the extraction of phenolic compounds from grape waste.

Liquid–liquid extraction. Liquid–liquid extraction is a mass transfer technique in which 1 or more solutes are added into a liquid solution (the feed solution), and this liquid is completely mixed with the solvent. This solvent has significant selectivity and affinity for 1 or more solutes present in the feed solution. Two different streams result from the contact reaction of 2 liquids, one is the extract, which contains the desired extracted solutes, and the 2nd, the raffinate, is the feed solution having less solutes (Müller and others 2008). This method is very useful for extracting phenolic compounds. Best results can be obtained by the selection of the most suitable solvent for the extraction. Industrial liquid by-products, such as liquids from the beverage industry, are the best materials for this technique.

Solid–liquid extraction. Solid–liquid extraction, also called leaching, can be defined as a mass transfer operation. In this technique, the solid matrix passes through a solvent that comes in contact with the matrix. Mass transfer operation can be increased by making changes in the boundary layer or diffusion coefficients and concentration gradients (Corrales and others 2009). This method is suitable for recovering crucial bioactive compounds like proteins from oilseed, sucrose from beet, phytochemicals from plants, oils and hydrocolloids from plant parts and algae, and polyphenols from fruits and vegetables. González-Montelongo and others (2010) compared analyses with various solvents, such as ethanol, acetone, methanol, water, ethanol:water or methanol:water, and found acetone:water as the best extraction solvent mix to extract anthocyanins and some other phenolic compounds from banana peel. Among ethanol, methanol, water, acetone, ethanol:water [1:1], methanol:water [1:1], and acetone:water [1:1], the acetone:water or ethanol:water were found to be the best solvents to extract tannins, flavonoids, and proanthocyanidins from mango

peel. For mango seeds, acetone:water or methanol were the best solvents for the same phytochemicals (Dorta and others 2012b).

There are many factors that may affect the extraction process, including flow rate, particle size, time, liquid–solid ratio, and temperature. Among these, time and liquid–solid ratio are the most significant factors (Rubilar and others 2003; Hayouni and others 2007). The common solvents for this method are water, ethanol, methanol, acetone, petroleum ether, and ethyl acetate (Amr and Al-Tamimi 2007; Caridi and others 2007), and methanol has been marked as the best solvent (Kapasakalidis and others 2006).

Conclusions

This review highlights the production, nature, and types of waste originating from fruits and vegetables. It also discusses the target bioactive compounds such as dietary fibers, phenolic compounds, flavors, enzymes, and organic acids present in FVW. It demonstrates the huge amount of losses and waste, not only the significant amount of nonedible materials, but also the huge amount lost and wasted due to lack of adequate handling operations such as inadequate field management, harvest, classification, transportation, storage (temperature and relative humidity) and marketing, and industry infrastructure, as well as waste generated due to discarding significant amounts for diverse reasons. These significant huge amounts of lost and wasted fruits and vegetables, and their components, represent not only losses of edible food materials but also the wasting of by-products including bioactive compounds of great potential benefits for various industries and uses. Extraction techniques, conventional and nonconventional, are described comprehensively. There is a need to utilize more novel techniques with respect to the waste materials to achieve higher retrieval rates of bioactive compounds. Extracted compounds can be used in food, pharmaceuticals, cosmetic, and chemical industries, and also in food research, and the development of functional foods.

Conflict of Interest

The authors declare no conflict of interest.

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