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Remodelingagro-industrial and food wastes into value-added bioactives and biopolymers

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ABSTRACT

Worldwide 1.3 billion tons of food is being wasted yearly from production to household level. This is an alarming situation as this food wastes create not only environmental and health issues but also economic crisis. Interestingly these food wastes are rich sources of a wide variety of bioactive molecules. Modern methods and technologies have to be adopted to utilize these food wastes for their efficient conversion into value-added products. Rather than dumping or burning the food wastes, these can be exploited as new sources for the production of useful bioactive molecules, which in turn will reduce the food wastes effectively. The bioactives and biopolymers produced from food wastes will be cost-effective, which, will enhance the market requirement. This review summarizes the existing and advancements in the extraction of bioactive compounds from food waste andmicrobial fermentation of food waste into polymers and its applications.

1. Introduction

Food is one of the basic needs of human beings. Enormous quantities of food are being wasted, starting from primary production tothe ultimate consumption of food. These agro-industrial and household food wastes are usually dumped in landfills or burned, which creates serious environmental and health issues. Parfitt et al. (2010) describes "food waste" as the food lost during the sale plus final usage by the consumer rather than lost during the food processing. Food loss occurs throughout the food chain up to theretail level,whereas food waste takes place inthe retail and utilization stage. A study conducted by the Food and Agriculture Organization of United Nations found that the one-third (approximately 1300 million tons yearly) of the total food produced for humans is being wasted worldwide (FAO, 2014). The reasons for food loss and waste could be attributed to many reasons including the bad climate, use of old techniques in harvesting, lack of storage facilities and poor usage bythe customer. The various modes by which food gets lost and wasted are summarized in Table 1.

Food losses and wastes can be reduced, but it cannot be avoided fully. Food waste includes plant waste which mainly contains peel, stems, seeds, shells, bran, pulp, residues;and animal wasteincludes waste from ananimal bred, dairy processing, seafood, and slaughter waste (Baiano, 2014). These food wastes are enormous sources of bioactive molecules with wide applications (Ng et al., 2020; Matharu et al., 2016; Laufenberg et al., 2003). Food wastes can be utilized as antecedents of various bioactive molecules such as polyphenols, dietary fibre, carbohydrates and proteins (Arun et al., 2017a, b; Lee et al., 2020). Thesebioactive molecules have enormous potential to be used as functional foods (Kumar, 2015), nutraceutical (Gupta et al., 2017), pharmaceutical (Baiano, 2014; Sundarraj and Ranganathan, 2018) and beauty care products (Ribeiro et al., 2013).

If food wastes are exploited for recovering bioactives and biopolymers, this will reduce the cost of production as well as efficiently reduces waste content. Hence effective strategies should be adopted to extract these economically important bioactive molecules using food wastes as resources. This review outlines the types and nature of the waste that arise from food, the bioactive components in the waste, their isolation techniques, the sustainable utilization of the bioactive compounds and production of biopolymer through food waste valorization.

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Table 1
Details about food loss and food waste.

Food lose/waste	Type	Mode	Percentage	Reference
Food lose	Agricultural lose	Damage, spillage through harvest and sorting process, Harvesting method, Harvesting timing	2–20 %	FAO, 2011 Ishangulyyev et al., 2019a, b Kumar et al., 2017
	Postharvest lose	Lose during handling, storage and movement from field to processing and distribution centres	up to 19 %	FAO, 2011
	Processing lose	Lose occurring at processing stage	0.5–25 %	FAO, 2011
Food waste	Distribution waste	Wasted in markets due to inappropriate storage, less demand and expiry period, Contamination of transportation, Inappropriate conveyance conditions	1–17 %	Kummu et al., 2012 Martinez et al., 2014
	Consumption waste	Loss and waste by the customer, Individual attitude, Cooking process and method, storage in household, over cooking, Household culture	1–30 %	Kummu et al., 2012 Ishangulyyev et al., 2019a, b Schanes et al., 2018

2. Global status of food waste

Along the chain of food supply, waste is produced at different loci that spread over from the production field to the household (Ishangulyyev et al., 2019a, b). Food waste is formed during the pre-harvest and post-harvest processes (Verma et al., 2019). The poor farming techniques and intense situations like awful climate and pest attacks cause pre-harvest losses (Parfitt et al., 2010). The post-harvest losses of food have been extensively studied by the Food and Agriculture Organization (FAO) of the United Nations. The recent report of FAO (2019) reveals that 14 % of food is being wasted all over the world, and in region-wise Central and Southern Asia together accounts for the highest rate (21 %) of food losses followed by Northern America and Europe (16 %). Australia and New Zealand region record the least food loss of 6 %. Lipinski et al. (2013) reported that 56 % of the world's total food waste is generated by the developed and industrialized nations of Europe, North America and countries like China, Japan and South Korea together. In the context of commodities, the FAO (2019) reports showed that higher rate of loss occurs among roots, tubers, and oilseeds (25%) followed by fruits and vegetables (21 %). Cereals and pulses lose only up to 8 %. The meat and animal products loss is 12 % (FAO, 2019) which mainly occurs due to improper packaging, storage, transportation, failing in consuming before the expiry date and dumping from markets after expiry dates not consuming before the expiration date (Priefer et al., 2013). The household waste mainly contains food waste, and awkwardly in developed nations, 40 % of food loss occurs at the consumer level (Gustavsson et al., 2011; Bond et al., 2013). The high carbon content of food waste is harmful as it is estimated that global food waste generates 4.4 gigatonnes of CO_2 which will significantly contribute to global warming (Emission Database for Global Atmospheric Research, 2012; Sims et al., 2014).

3. Extraction of bioactive compounds from agricultural and food wastes

The bioactive molecules such as polyphenols, antibiotics, pigments and alkaloids; and biopolymers such as dietary fibre, proteins, polysaccharides and lipids can be extracted from food wastes. These bioactives possess biological properties such as antioxidant, anti-diabetic, anti-inflammation,cardiovascular protection and anticancer activities. Biopolymers are utilized in water treatment, biomedical zone, energy sector, andthe food industry. If the procedures for extracting these molecules are economically viable, increased attention will be drawn towards food waste as a source.

The active compounds present in food wastes have to be extracted from the core matrix through physical, chemical and biochemical methods. Different techniques have been used for the extraction of bioactives, and these processes repeatedly get modified for better production. Agro-industrial residues are rich in cellulose, hemicellulose and lignin. These polymers interfere with the extraction procedures, and hence some pre-treatment procedures have to be done for proper extraction of bioactives from these food wastes.

Physical, chemical and biological methods are employed before extraction is initiated. Physical pre-treatment includes size reduction by milling, steam treatment, hydrothermolysis, microwave an ultrasonic treatments (Yoo et al., 2011; Zheng and Rehmann, 2014; Oberoi et al., 2011; Sarkar et al., 2012). Treatment with alkali, acid, calcium hydroxide, ammonia, organic solvents and hydrogen peroxide is usually followed in chemical pre-treatments (Sills and Gossett, 2011; Kaur et al., 2012; Liao et al., 2007; Holtzapple et al., 1992; Nakamura et al., 2004; Ichwan and Son, 2011). Biological pre-treatment involves treating with enzymes directly or with the microorganisms, which produces enzymes that can degrade cellulose and lignin (Xiao et al., 2012).

Pre-treatment matrix is more acquiescent to extraction procedures.However, there is no single extraction technique and it has to be determined based on waste content, uniformity, aggregation phase and many more (Socaci et al., 2017). Some of the extraction techniques are discussed below and the details of bioactives extracted by these extraction methods are summarized in Table 2.The comparative advantages and disadvantages of different extraction methods are also included.

3.1. Solid-liquid extraction

Solid-liquid extraction, described in AOAC protocols (Method 43.290, AOAC 1990a, b), is the base of several analytical procedures that permits removal of soluble constituents from solids using water and/or organic solvents. This method works on the principle of osmosis and diffusion by which the extractable components present in a solid matrix will move to the liquid in which the matrix is immersed (Naviglio et al., 2019). This is one of the oldest and commonly used techniquesutilized to extract bioactives. At optimized conditions such as pH, temperature, weight/volume ratio, the polarity of solvents solid-liquid extraction gives better yield (Pompeu et al., 2009). The use of harmful solvents and the long time period for the extraction are the major drawback of this technique (Proestos and Komaitis, 2008). Nevertheless, this technique has wide applications and can be incorporated with other extraction techniques to overcome the drawbacks.

3.2. Soxhlet extraction

Soxhlet extraction (Method 43.290, AOAC 1990a, b) like solid-liquid extraction works on the principle of osmosis and diffusion, along with heating the system. This method washes the core material continuously, which aids the rapid solubilization of the desired component. This technique is not suitable for the extraction of heat liable

Table 2
Details of the bioactives extracted from food wastes by various extraction methods.

Extraction Method	Compounds extracted	Source	Advantages	Limitations	Reference
Solid-liquid extraction	Pectin	Apple pomace, Citrus peel, Sugar beet, Sunflower heads, wastes from tropical fruits	Separation rate is faster Easy handling with little manual efforts High reproducibility	Suitable for natural compounds from plants	Waldron (2009); Abd-Talib et al., 2014
	Flavonones	Citrus peels and residues from segments and seeds after pressing			Waldron (2009)
	Dietary fibre	Apple pomace			Schieber et al. (2003)
	Phenolic compounds	Apple pomace, Plantain inflorescence, spent cumin, pomegranate peel			Kołodziejczyk et al. (2007); Ieri et al. (2011)
	γ-oryzanol	Rice bran			Oliveira et al. (2012)
	β-glucans	Barley bran			Izydorczyk and Dexter, 2008
	Lignans	Flax seeds			Sainvitu et al. (2012)
	Proteins	Hazelnuts meal - oil crops			Aydemir et al. (2014)
	Polysaccharies	Brewers' spent grain - cereals			Niemi et al. (2012a)
Soxhlet extraction	Lipids	Brewers' spent grain - cereals	Widely used classical Technique Basic model and easy to handle	Time consuming Not eco-friendly and need large quantities of solvents	Niemi et al. (2012b); Azmir et al., 2013
Microwave assisted extraction	Phenolic acids	Wheat bran	Highly selectable towards desired extracts High yield with less extraction time Economical compared to solvent extraction Operation is simple and highly economical compared to supercritical fluid extraction Extraction time is short compared to ultrasonic-assisted extraction	Expensive Difficult handling compared to ultrasonic-assisted extraction Not eco-friendly due to involvement of solvents Extraction yieldd is less for non polar compounds	Oufnac (2006); Kumar et al., 2016
Supercritical fluid extraction	Caffeine	Green tea leaves	Eco-friendly due to less involvement of solvent Provides high mass transfer due to low viscosity and high diffusion coefficient than liquid solvent extraction Highly suitable for volatile compounds	Costly and not suitable for polar compounds	Perva-Uzunalić et al. (2004b); De Marco et al., 2018
	Lycopene and β-carotene	Tomato pomace			Baysal et al. (2000)
	Essential oils	Chamomile			Kotnik et al. (2007)
	Capsaicinoids and colour components	Chilli pepper			Perva-Uzunalić et al. (2004a)
	Oil	Rice bran			Perretti et al. (2003)
	Lipids	Grape seeds			Prado et al. (2012)
	Polyphenols	Grape seeds			Agostini et al. (2012)
	Carotenoids	Sea buckthorn seeds			Kagliwal et al. (2011)
Ultra sound assisted extraction	Polyphenols	Rape seeds, apple pomace	High yields Save energy and power Less chemicals	Proper frequency optimisation is required for maximum yield.	Yu et al. (2016); Pingret et al. (2012); Singh et al, 2017
	Carotenoids	Citrus peel			Sun et al. (2011)
	Proteins	Rape seed meal			Yu et al. (2016)
Steam current distillation	Essential oil	*Flaveriabidentis*			Wei et al. (2012)
Pulsed electric field extraction	Phytosterols	Maize	High Yiels and less time Suitable for heat labile compounds	High level optimisation is needed	Guderjan et al. (2005)
	Anthocyanins	Grape skin			Corralesa et al. (2008)
Accelerated solvent extraction	Polyphenols	Potato peel			Luthria (2012)
Subcritical water extraction	Polyphenols	Canola seed meal			Hassas-Roudsari et al. (2009)
	Catechins and proanthocyanidins	Wine related products			Garc´ıa-Marino et al. (2006)

(*continued on next page*)

Table 2 (*continued*)

Extraction Method	Compounds extracted	Source	Advantages	Limitations	Reference
Enzyme assisted extraction	Luteolin and apigenin	Pigeon pea	Eco-friendly No hemicals High Yield	Enzyme cost is high Economically not feasible for scale up	Chandini et al. (2011)
	Gallic acid	Agricultural waste			Curiel et al. (2010)
	Flavanoids	Ginkgo biloba leaves			Chen et al. (2010)
	Polysaccharides	Brewers' spent grain, Palm kernel cake			Niemi et al. (2012a); Ng et al. (2013)
	Polyphenols	Tomato pomace and skin			Waldron (2009)
	Dietary Fibre	Plantain inflorescence, spent cumin			Arun et al. (2018); Arun et al. (2017a, 2017b)
Rapid solid liquid extraction	Polyphenols	Saffron, Cagnulari grape pomace			Ferrara et al. (2014); Posadino et al. (2018)

biomolecules (Jensen, 2007) and uses a fair amount of energy, also, and this is important in scaling up.

The main disadvantages of classical extraction methods are less purity, use of costly solvents, not eco-friendly,time-consuming, degradation of heat-sensitive compounds and less extraction selectivity. To overcome these limitations, several novel techniques have been developed.

3.3. Microwave-assisted extraction

Microwave-assisted extraction uses microwaves to heat the matrix-solvent mixture to enhance bioactive extraction. These electromagnetic waves act on the total volume rather than heating the surface and directly heat the matrix-solvent mixture, which in turn reduces the time for extraction. This method is preferred over the solid-liquid system for the extraction of plant bioactives, and this technique is not suitable for scale-up due to the complex mass transfer involved (Chan et al., 2015). Extraction of natural products and volatile oils by this method has been patented (Pare et al., 1991; Pare, 1994). This method can extract natural compounds efficiently and rapidly as compared to classical extraction techniques.This technique is considered as eco-friendly and avoids the use of harsh solvents. Dorta et al. (2013) compared microwave-assisted extraction and conventional solvent extraction for bioactive extractions from mango peel. They reported that they achieved 6 times higher amount of bioactive molecules than the conventional method.

3.4. Supercritical fluid extraction

Supercritical fluid extraction uses an extraction solvent which is supercritical (Sharif et al., 2014). The supercritical carbon dioxide (in-between gas and liquid) is preferably used in this technique. The fluid can be regulated efficiently for extraction purpose, and this nature allows the user to remove the fluid from the matrix in a better way when compared to other solid-liquid extraction protocols. In this technique fluid with higher permeability spread over the matrix in a faster rate. The system works at room temperature and is suitable for heat-labile bioactives, especially non-polar compounds. However, the system is very costly and complicated.

3.5. Ultrasound-assisted extraction

Ultrasonication uses high-frequency sound waves which cause expansion and compression cycles in the matter. Ina liquid medium, the waves produced by the sound create small bubbles which grow and collapse. Towards matrix, the bubble collapse hasa strong impact on the solid surface and causes solvent penetration, thus triggering the discharge of bioactives (Luque-Garcia and de Castro, 2003).

3.6. Steam current distillation

Steam current distillation is used for the extraction of essential oils works on the principle that the vapour pressure of the volatile oil makes them separated from the matrix. Steam is forcefully passed to a container containing the matrixincreasing the vapour pressureof the components which make them to release the matrix in gaseous form. This is further condensed and collected.

3.7. Pulsed electric field extraction

When a pulsed electric field above 1 V (above trans-membrane potential) was applied over cells, membrane depolarization occurs, and micropores are formed in the cell membrane which facilitates the release of intracellular bioactives from the cells (Fincan et al., 2004; Ho and Mittal, 1996). This technique is suitable for the extraction of heat-labile compounds.

3.8. Accelerated solvent extraction

This extraction technique keeps the solvent in the liquid phase at temperatures higher than the boiling point. In effect, this increased temperature speeds up the release of bioactives from the matrix in a better time period. This technique is adopted to extract constituents from core matrix with intricate chemical-physical nature (Naviglio et al., 2019).

3.9. Subcritical water extraction

Water under high temperature (100–374 °C) and high pressure (10–60 bar) wereused to carry out the extraction. At these conditions applied the dielectric constant of water become similar to that of some organic solvents. Thus this technique can replace the organic solvent for the extraction of non-polar bioactives from various matrices (Plaza et al., 2010).

3.10. Enzyme assisted extraction

Enzymes can be used to break the cell wall and membrane to release the bioactives. This is an efficient method for the extraction of bioactives, as this method can avoid the usage of organic solvents. Enzyme assisted extraction, using enzymes such as cellulase, pectinase and hemicellulase; facilitates the release of bound bioactives such as polyphenols which are foundto some extent inbound with cell wall matrix (Fu et al., 2008; Puri et al., 2012).This method is considered as an environment friendly for the extraction of oils and natural bioactives compounds since water is used instead of costly solvents (Puri et al., 2012).

3.11. Rapid solid-liquid extraction

Naviglio (2000) established this technique which does not require heating for better yield. The filter bag with dried matrix was placed in Naviglio extractor with pressure 8–9 bars at room temperature. Depending on the matrix, this cycle was repeated up to 30 times to complete exhaustion of the matrix.

4. Valorization of waste and by-products from the agro-food industry using fermentationprocesses and enzyme treatments

A significant amount of food wastes have been disposing of continuously by the food processing industries in the last few decades. Reports suggested that 14 million metric tons of wastes are generated by food processing industries (Parfitt et al., 2010). Ajila et al. (2010) reported that approximately 30 % of food wastes are emerging from fruits and vegetable processing sector. FAO reports (2014) showed that the Philippines, China, India and USA as the leading food waste producers. As discussed in the introduction,these food wastes cause serious problems and therefore it is necessary to valorize these food wastes into value-added products or to use it as a source of extracting various bioactives (Saini et al., 2019).

Bioactive molecules are plant-derived products which exhibit various biological properties (Studdert et al., 2011). Interestingly these molecules are abundantly present in food wastes, and these can be extracted by various extraction techniques discussed earlier (Kumar et al., 2017; Lavelli et al., 2017; Maina et al., 2017; Pagano et al., 2017). These food wastes are enriched with economic as well as health significant constituents such as sugars, vitamins, minerals, enzymes, pigments, flavours, functional ingredients, micronutrients, nutraceuticals, active pharmaceutical ingredients, phytochemicals, biofuel and biomaterials (Lai et al., 2017; Sadh et al., 2018).

Over 20 million metric tons of animal wastes are generated annually in Europe (Henchion et al., 2016). At present, these wastes are used as fertilizers and animal feed (Alao et al., 2017). Since these animal wastes are rich in proteins, efficient exploitation can increase the income of the slaughter industry and reduces pollution hazards (Henchion et al., 2016; Toldra et al., 2016). Enzymatic hydrolysis of animal waste yields protein hydrolysates, which possess biological properties and owns solubility, foaming and emulsifying properties that allows it to use as food ingredients (Fu et al., 2018; Lafarga and Hayes, 2014; He et al., 2013).

Fermentation is one of the primaeval techniques utilized for generating value-added products. Solid-state, submerged and liquid fermentation are most commonly used fermentation techniques. Among these, solid-state and submerged fermentation methods are performed for extracting economically important bioactives using substrates such as food wastes (Subramaniyam and Vimala, 2012).

4.1. Solid-state fermentation

Solid-state fermentation is initiated by growing microbes (bacteria/fungi) on solid substrates which force the microbes to give maximum attention to the substrate. This technique is effective in waste valorization as the microbes successfully convert waste to value-added products (Thomas et al., 2013; Chen and He, 2012). Low energy consumption and high yield of value-added products from wastes make this process very attractive (Yazid et al., 2017). This process is of two types – (i) substrate act as support as well as a nutrition source, and (ii) substrate act as support in semi-liquid medium (Pandey, 2003). Solid-state fermentation is particularly gaining attention due to its comparatively easy process, use of low-cost biomaterials with minimal pretreatment requirement, less wastewater production, and provides a supportivemicroenvironment for microbial growth (Wang and Yang, 2007).Solid-state fermentation has been reported to extract proteins, lycopene, and phenolic contents from food wastes (Madhumithah et al., 2011; Dhanasekaran et al., 2011; Jamal et al., 2016; Schmidt et al., 2014). Bioethanol, indol-3 acetic acid, protease, xanthan, phenolic content, antioxidants, neomycin, rifamycin, citric acid are a few of the compounds produced by solid-state fermentation (Hossain and Fazliny, 2010; Swain and Ray, 2008; Chutmanop et al., 2008; Vidhyalakshmi et al., 2012; Sousa and Correia, 2012; Dulf et al., 2017; Vastrad and Neelagund, 2011, 2012; Ali and Vidhale, 2013).

4.2. Submerged fermentation

In this type of fermentation, the substrate is liquefied or immersed in the water source. The only disadvantage is that the method requires more space, energy and water. This method is widely used for enzyme production than the solid-state fermentation. Enzymes such as pectinase, amylase, galactouronase, cellulase have been produced from food wastes using submerged fermentation (Knob et al., 2014; Vidyalakshmi et al., 2009; Debing et al., 2006; Budihal and Agsar, 2015; Nema et al., 2015).

5. Potential use of bioactive compounds from waste in the food, cosmetic andpharmaceutical industry

Extraction of bioactives from food waste mainly generates income for food, cosmetic and pharmaceutical industries due to the low cost of source and abundant presence of these molecules in the discarded waste. As mentioned earlier, bioactive molecules possess certain health beneficial effect, which makes them useful as ingredients in developing functional foods, nutraceuticals, cosmetics and pharmaceutical products. Now consumers are more health-conscious, and hence bioactives incorporation in food cosmetics and nutraceuticals have been gaining more importance.

Functional foods are made to enhance health and reduce the risk of developing diseases. Bioactives are added to fortify the food with other health beneficial property, and such foods are generally coined as functional foods. The food wastes are rich in dietary fibre, proteins,

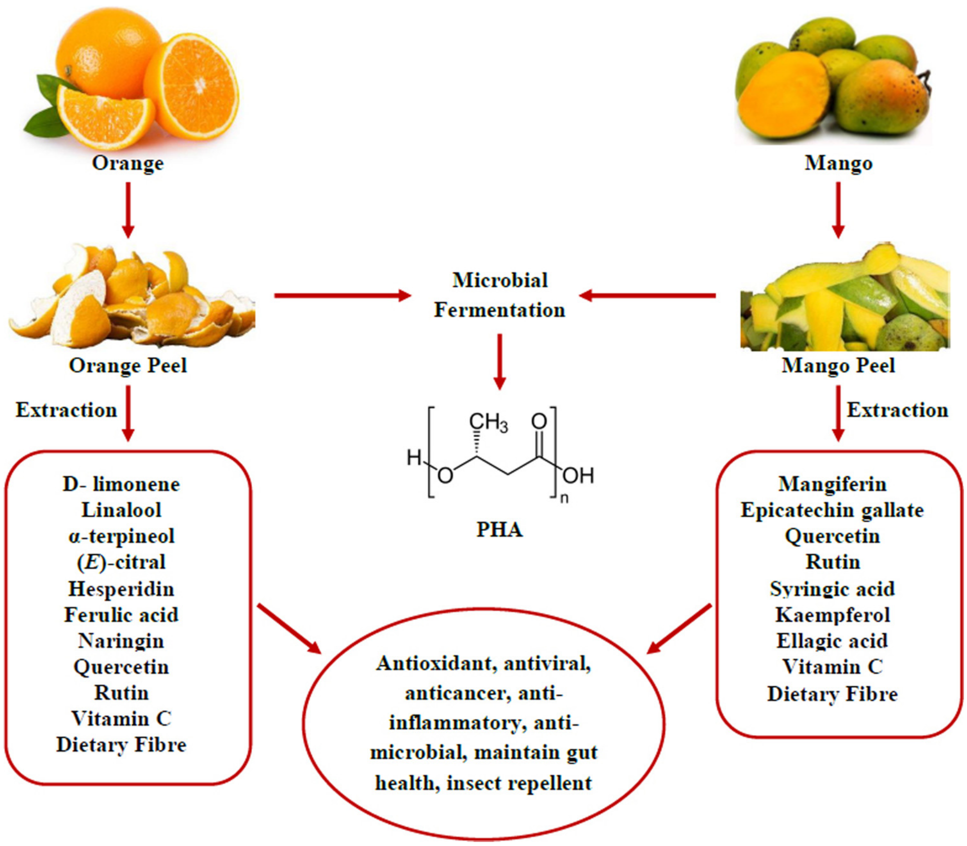

Fig. 1. Schematic representation of valorization of orange and mango peel.

energy, minerals, vitamins and antioxidants that have been recognised as a functional food ingredient. The biomolecules extracted from agricultural and animal wastes can be utilized to manufacture functional foods (Baiano, 2014). The bioactive components such as sterols, tocopherols, carotenes, terpenes and polyphenols extracted from food waste possess antioxidant credential. Hence, these value-adding ingredients extracted from food waste can be used to formulate functional foods with enhanced antioxidant property. (Kalogeropoulos et al., 2012).

Plantain inflorescence, which is discarded as the agricultural residue is rich in dietary fibre and polyphenols and the solvent extracts possess antioxidant, antidiabetic, cardiovascular protection an anticancer efficacy (Arun et al., 2017a, b). The polyacetylenes falcarinol and falcarindiol derived from carrots demonstrated anti-inflammatory effect as it suppresses NFκB (Teodoro, 2019). Fish protein hydrolyzates are rich in bioactive peptides and have anticoagulant, anticancer and hypocholesterolemic potential. Moreover, fish oils are excellent sources of omega-3 fatty acids, while crustaceans and seaweeds contain carotenoids and phenolic compounds with antioxidant properties (Lordan et al., 2011).Curcumin, an important molecule with diverse biological applications, extracted from Curcuma species, is widely used by the traditional medical practitioners (Prakash et al., 2017). The extracts of soy, tomato spinach, oats are rich in isoflavones, lycopene, lutein, an β-Glucanrespectively and are used as food ingredients to enhance human health (Hasler, 2002). Biologically active sulfur components - allicin and allylic sulfides present in *Allium sativum* are known to reduce blood pressure (Silagy and Neil, 1994). The essential oils are receiving considerable notice of food industries due to its antimicrobial and antioxidant potential (Prakash et al., 2017). Dietary fibres are effective in stimulating the growth of probiotic bacteria and prevent cardiovascular diseases (Arun et al., 2019; Beer et al., 1995; Bouhnik et al., 1997). Linolenic acid inhibits carcinogenesis, and decrease body fat (Belury, 1995; Sébédio et al., 2003). Terpenes such as carotenoids, and limonoids are biological antioxidants and have a cryoprotective effect (Snodderly, 1995; Meister et al., 1999); and saponins have an immunostimulatory and cholesterol-lowering effect (Rao and Gurfinkel, 2000). Phenolic acids, flavonoids and lignans have antioxidant property, lowers the risk of colon cancer and heart diseases (Ferguson et al., 2005; Mirmiran et al., 2009; Arts and Hollman, 2005).The phenolic compounds, carotenoids, vitamin C and dietary fibre present in mango peel are known to lower the risk of cancer, cataracts, Alzheimer's disease and Parkinson's disease (Ayala-Zavala et al., 2010).

Bioactive molecules obtained from winery wastes exhibit *in vitro* and *in vivo* biological activities. They are successful agents for prevention of degenerative processes during their assimilation in functional foods, nutraceuticals, and cosmetics (Teixeira et al., 2014). These are commonly utilized for the production of pharmaceuticals and as food additives to increase the functionality of foods (Ayala-Zavala et al., 2010). Rudra et al. (2015) had reported the usage of agro-industrial residues for the development of value-added products such as cosmetics and medicines. Cellulose from agro-industrial residues was used in manufacturing pharmaceuticals and cosmetics (Klemm et al., 2005). Ferulic acid extracted from pineapple peel is used in the food and cosmetic industry (Rudra et al., 2015). Lycopene from tomato pomace, tyrosol from olive cake, hesperidin and naringin from citrus pulp, quercetin from apple pomace, proanthocyanidins and resveratrol from grape pomace, ellagic acid from pomegranate pulp, anthocyanins from onion pomace, alliin and allicin from garlic extract, and gallic acids from mango pulp could be potentially used as skin photoprotectants (Simitzis, 2018; Menaa et al., 2014; Lorencini et al., 2020).The tyrosinase inhibitory activity of polypeptides from oyster shell attributes skin-whitening effects (Baiano, 2014).

Antioxidants extracted from food wastes such as citrus wastes and lobster processing wastes have the potential to use as pharmaceuticals (Mahato et al., 2018; Nguyen et al., 2017).Chitin derived from lobster processing wastes has numerous applications in food, agriculture, healthcare products, environmental sector, pharmaceuticals, and biomedicine (Kaur and Dhillon, 2013; Muzzarelli, 1989; Sandford, 1989; Synowiecki and Al-Khateeb, 1997).Collagen isolated from various food wastes can be used for drug delivery (Friess, 1998). Gelatin is used as a natural antioxidant and antihypertensive agent, and it also and to improve the absorption of dietary calcium (Choonpicharn et al., 2015). Melatonin, extracted from the pineal gland, is used for the treatment of schizophrenia, insomnia, and other mental diseases (Morera-Fumero and Abreu-Gonzalez, 2013). Bile, extracted from the gall bladder, is used for treating bile tract disorders and constipation. Calcium carbonate from oyster shells is used as calcium increment (Baiano, 2014).

6. Current status of food waste valorisation around the world: Special reference to orange and mango peel

Peels are one of the important by-products from fruits and some vegetables and are an enormous source of bioactive compounds and dietary fibre (Fig. 1) (Arun et al., 2016, 2017a, b; Arun et al., 2018). Peel from citrus (50 %), banana (35 %), mango (35 %) and guava (10%) are typically wasted without use (Gupta and Joshi, 2000). Citrus fruits (oranges, lemons, clementines, limes, grapefruits, and tangerines), are one of the important fruit commodities widely consumed by humans. 70 % of the world's citrus production is owned by countries such as Brazil, USA, India, China, and Japan. Peel accounts for 50 % of the weight of the citrus. It is estimated that from 94.8 million tons of citrus fruits produced globally,over 31.2 million metric tons of citrus fruits are processed which results in generating 15.6 million metric tons of peel (Lin et al., 2013). Sugars, cellulose, hemicellulose, pectin and D-limonene are important chemical constituents present in citrus peels. Citrus peels have been valorised to produce pectin, pectic enzyme, dietary fibre, bioethanol, methane, succinic acid and D-limonene (Lin et al., 2013). D-limonene is an important compound with an antiviral (Nagy et al., 2018; Astani and Schnitzler, 2014), anticancer (Yu et al., 2018; Mukhtar et al., 2018) and anti-inflammatory (Yu et al., 2017; d'Alessio et al., 2013) activities. India is the largest producer of mangoes, and these are processed to prepare various products (Berardini et al., 2005). Peel and kernel, which account for 30–55% of the mango are the major waste generating from mango processing industries (Puligundla et al., 2014). Mango peel contains pectin, cellulose, hemicelluloses, lipids, proteins, polyphenols and carotenoids (Ajila et al., 2007). Mango peel has been valorised for the production of pectin (Kumar et al., 2012), phenolic compounds (Palmeira et al., 2012), ethanol (Reddy et al., 2011), pectinases (Kumar et al., 2012), cellulase (Saravanan et al., 2012), lactic acid (Jawad et al., 2013), and biogas (Walia et al., 2013). The main bioactive compounds isolated from mango peel were flavanols (epicatechin-gallate, epigallocatechin-gallate), flavonols (quercetin-3-*O*-glucopyranoside and rutin), and phenolic acids (gallic acid, o-coumaric acid, and syringic acid) (Coelho et al., 2019).

7. Safety aspects of animal waste for valorization

The industries which produce livestock commodities such as milk, meat, poultry, and fish produce enormous wastes that are unsafe to the environment if not managed properly (Ogbuewu et al., 2012). The water effluent expelled by these industries possess high BOD/COD level and is rich in nitrogen. Strictly regulated pre-treatment protocols are implemented before the disposal of livestock wastes. These pre-treatment protocols usually involve incineration (if the animals are diseased or infected, and parts that are not suitable for consumption), anaerobic digestion (dead animals, manure) and finally, recovery of value-added products from discarded products (improper packaging, storage and expiry date) (Meher et al., 2006; Kosseva et al., 2003).

8. Polyhydroxyalkanoates (PHA) production using food waste as a carbon source

Among the different classes of bio-products derived from food waste are the polyhydroxyalkanoates (PHAs), a class of very interesting biopolymer produced by different microbial cells in the form of granules inside the cytoplasm. Extensive studies have been done so far for the production of PHA using food waste. This includes optimization of PHA accumulation, yield and production capacity. Carbohydrates like glucose, fructose, maltose, lactose and alkanes like hexane, octane, alkanoic acids like acetic acid, propionic acid, butyric acids, and oleic acid, alcohols like ethanol, methanol, and glycerol, gases like methane and carbon dioxide, and different acids are considered as key carbon sources for the biosynthesis of PHA (Poli et al., 2011). Severalvaluable carbon sources are employed in the industrial production of PHA such as pure glucose and sucrose and alkanes, and fatty acids. The costly and unaffordable nutrients like amino acids and phosphate are not economical, and this results in difficulty in the execution of many developed bioprocesses. Cost-effectiveness is very important for developing and implementing bioprocesses. So the selection of affordable nutrients such as carbon and nitrogen nutrients plays a key role in microbial fermentation (Liang and Qi, 2014).

Fruits and vegetables can be a potentialcarbon source for the fermentativeproduction of PHA. Most of the fruit products (Apple juice, citrus juice) are prepared through the extraction of 50% of fruits. This resulted in the generation of fruits residues which remain as waste. These wastes contain large amounts of sugars and low amount of proteins. Recently jambul seeds were employed as sole carbon sources for the production of PHA and production reached 41.7 g/l and 42.2 % respectively (Preethi et al., 2012). Pomace fruits were investigated for PHA production by Follonier et al. (2014). The achieved concentration of biomass was 10.2 g L^{-1}, which contain12.4 wt % mcl-PHA. Ganzeveld et al. (1999) used fruits and vegetable waste to produce PHB by the fermentation of *R. eutrophus* with the oxygen-limited atmosphere. The working volume of fermentor was 750 ml, with the controlled temperature at 30 °C. Bacterial PHA production can be carried out by using either pure or mixed microbial culture. Mixed microbial fermentation with high PHA production capacity has been recommended as a solution for the reduction of the costs of pure cultures and is highly efficient for the production of PHA from food waste (Colombo et al., 2017). The concentration obtained was 1.1 g PHBV, or 40 % (w/w) of the cell dry weight, was obtained. Potent producers of PHA are listed in Table 3, and engineered bacteria which produces PHA is listed in Table 4.

8.1. Microbial fermentation techniques for PHA production from food waste

With the advent of a large number of cultivation techniques for the production of PHA, the type of bacterial fermentation plays a key role in the mass production of PHA. Industrial fermentation technology uses batch and fed-batch fermentation technologies. For the production of PHA, the fed-batch method was proven as the best method which yields more amount of PHA compared to the batch process. The N/P ration is less in the fed-batch process, and thus cell density can be monitored easily by adjusting carbon feeding rate. Thus carbon source concentration can be adjusted to give high osmotic pressure for bacteria. Hafuka et al. (2011) reported a two-stage cultivation technique had been utilized for the mass cultivation of copolymer of PHB-P(3HB-co-3 HV). In this technique, bacteria are allowed to grow up to a predetermined cell mass without any nutrient limitation. Then cells are allowed to grow to another cultivation medium with fewer nutrients and utilize only the supplied single carbon source for the accumulation of PHA. The main advantage is that cells are not able to divide during the scarce nutrient stage. However,an increase in cell size and volume due to intracellular production of PHA.

Many bacteria produce PHB as a consequence of physiological

Table 3
Wild type bacteria producing PHA from food waste.

Strain	Biopolymer	Food source	Biopolymer percentage	Reference
Cupriavidus necator	PHB	Pressed juice from oil palm	30	Zahari et al. (2012)
Cupriavidus necator	PHB	Wheat bran and Rape seed meal	78.9	Kachrimanidou et al. (2016)
Thermus thermophiles HB8	PHA	Whey	35.6	Pantazaki et al. (2009)
Cupriavidus necator H16	PHB	Soy bean and rapeseed oil	79	Taniguchi et al. (2003)
Psuedomonas	PHA	Corn oil	35.63	Chaudhry et al. (2011)
Cupriavidus necator	PHB	Spent coffee Grounds oil	89	Obruca et al. (2014b)
Bacillus firmus	PHB	Rice straw	89	Sindhu et al. (2013)
Psuedomonas	PHA	Molasses	20.63	Chaudhry et al. (2011)
Burkholderiasp	PHB	Sugarcane bagasse	48	Lopes et al (2014)
B. megaterium	PHA	Cheese whey	51	Obruca et al.(2011)
Methylobacterium sp.	PHA	Cheese whey	67	Nath et al (2008)
H. pseudoflava	PHA	Cheese whey	40	Koller et al (2007)

stress. Bacterial like *Ralstoniaeutrophus* and *B. megaterium*are the potent producers ofPHB upon stress (Laycock et al., 2014). SSF (Solid State Fermentation)can be established without water or less water (Pandey, 2003). SSF has the advantage of less energy uptake, high productivity, less process waste generation, decreased catabolic repression and generation of value-added products (Hölker et al., 2004). Sustainable utilization of waste can be achieved through the implementation of SSF, which can use a different variety of food and agro-industrial wastes as substrates for the fermentation process.

8.2. PHA production using whey protein

Whey is a by-product of dairy industriesand is one of the most interesting food wastes. It is the by-product of cheese making industry which contains carbohydrate lactose, fats, proteins, minerals, vitamins, and other essential components for bacterial growth. Many of the surplus whey has to be disposed of, and this disposal leads to severe environmental issues due to its high pollutant characteristics, and majority of whey is disposed of in wastewater treatment (Prazeres et al., 2012; Pescuma et al., 2015).

Recently one study proved that 1.5×10^8 tons of whey are producing worldwide (Koller et al., 2007). When proteins like lactoferrin are produced using huge whey volume of whey retentate remains as waste and need to be disposed of. Moreover, acid whey is the by-product of many dairy products like cream cheese, cottage cheese etc. Processing of acid whey is difficult due to its highly acidic nature (Lievore et al., 2015; Ryan and Walsh, 2016). So efficient whey is a major issue faced by the dairy industry, and thus it makes potential substrate for a carb for PHA production at industrial scale (Girotto et al., 2015). The inefficient disposal of a large volume of whey into the environment can destroy the chemical and physical nature of the soil, groundwater and atmosphere (Zhong et al., 2015). *C. necator* is the best reported highest producer of PHA, but this bacteria is not capable for lactose or galactose utilization (Gomez et al., 2012). *C. necator* was engineered to express β-galactosidase and galactokinase (Pries et al., 1990). Still lactose hydrolysis could not be improved. So recombinant *E. coli with* the *C. necator* PHA biosynthetic genes which utilize glucose is considered as potential bacteria for PHA production from whey (Lee et al., 1997).

8.3. PHA from waste oil

Waste oils have been used in industries and for food production and are no longer viable for human use. They are a potential substrate for the production of PHAs. The main advantages of these oils are ready to use nature, and it doesn't require any pre-treatment and can be used directly in growth media. The potential of *Cupriavidus necator* H16 to transform waste oils and tallow to PHAs has been reported by Taniguchi et al. (2003) The highest PHA accumulation was achieved in this study when palm oil was used as the substrate (6.8 g/l and 80 % PHB accumulation).

In another study by Fukui and Doi (1998), various plant oils or oleic acid were used as the substrate for PHA production by *C. necator* H16. The bacteria were also tested on other different oils like olive, corn etc. The copolymer of 3HB with 5 mol% (R)-3-hydroxyhexanoate, P(3HB-co-3HHx) was produced by the engineered strain of *C. necator* from soybean oil (Kahar et al., 2004). The fermentation medium used was a mineral salt medium, and the ammonium chloride concentration (Initial) was 4 g l^{-1}. Ammonium chloride was added intermittently to fermentation medium to restrict nitrogen depletion. The initial concentration of Soybean oil was 20 g l^{-1}. The final content of P(3HB) was 85–95 g l^{-1} and a PHA was 71–74 % (w/w). Füchtenbusch et al. (2000) cultivated *P. oleovorans and R. eutropha* with waste for PHA production under aerobic conditions. Recently Vastano et al. (2019) produced PHA from waste frying oil using recombinant *Escherichia coli* and native *Pseudomonas resinovorans,* and they achieved 1.5 g L^{-1} of medium chain length PHAs and conversion yield of 80%.

8.4. PHA production from spent coffee grounds (SCG)

Spent coffee grounds are the by-product of coffee processing. The major content (9–15%) of spent coffee grounds is oiled and can be utilized for further valorization purposes (Al-Hamamre et al., 2012). The unspent content of the coffee grounds is mainly biomass that can be hydrolysed and used for the production of PHAs. Obruca et al. (2014a) reported the use of *Burkholderia cepacia* for the production of PHA. In another study by Obruca et al. (2014b) compared the SCG with other waste generated oil in *C. necator* H16 for the production of PHA and concluded that SCG served as the best substrate. In thelaboratory flask

Table 4
Engineered PHB producing organisms from food waste.

Food waste	Bacteria	Construct	Source	PHA	Biomass	% accumulation	Reference
Whey	*E.coli*	pJC4	*Alcaligenes latus*	PHB	119	80	Ahn et al, 2000
Whey	*E coli*	pJP24K	*Azotobactersps*	PHB	70	72	Nikel et al, 2006
Whey	*E.coli*	–	*Pseudomonas hydrogenovora* DSM 1749	P(3HB)	1.27	12	Koller et al., 2007
Soy waste	*E. coli*	pUC19	*C. necator*	PHBV	–	23	Law et al, 2004
Starch	*Aeromonassp*	pRK415H16	C. necator	PHB	1.83	32	Chien and Ho (2008)
Starch	*E coli*	pTAmyl, SKB99, pLW487, pET24ma	*Panibacillus sp. Ralstoniaeutropha*	PHB	1.24	57.4	Bhatia et al, 2015

level experiment with SCG oil resulted in the biomass content of 14.2 g/land PHB content of 70 %. The scale-up of the process enhanced the biomass weight to 55 g/l and PHB concentration to 89 % in fed-batch fermentation. The main disadvantage of using SCG is its foaming nature. In another study, Obruca et al. (2015) extracted oil from SCG and efficiently transformed into PHA employing *Cupriavidus necator* H16. The remaining solid residues after oil extraction can be convertedinto fermentable sugars, which can be further used as a carbon sourcefor the production of PHAs by*Bacillus megaterium* (YP/S = 0.04 g/g or *Burkholderia cepacia* (YP/S = 0.24 g/g).

8.5. PHAs production from sugar beet and molasses

Sugarcane industry generated waste has been investigated for the production of PHA. Molasses are residual syrup which is the by-product from sugar refining mills. This contains high sucrose and is not good for consumption (Gomez et al., 2012). Chaudhry et al. (2011) compared different sugar industry generated waste for the production of PHA using a Pseudomonas species and found that molasses as the best substrate with the PHA accumulation of 20.63–35.63 %. In another study by Kulpreecha et al. (2009) *Bacillus megaterium* BA-019 was cultivated in molassesand achieved cell weight of 72.7 g /1 and PHA content of 42 %. Sugar beet is another source of high sucrose. Wang et al. (2013) tested*Alcaligeneslatus* with sugar beet as the carbon source along with other nutrient supplements and achieved biomass content of 10.3 g l1 and a PHB yield of 38.66 %.An Italian company has developed several PHA polymers, Bio-on, based on sugar beet (Babu et al., 2013; Dietrich et al., 2017).

9. Future prospective

The food loses, and food waste occurring throughout the food chain from production to household level should be minimized by exploiting the waste by producing value-added products. Even though various methods are there for extraction of bioactives and biopolymers from food waste, new technologies should be dug out for maximum yield with less investment. This has to be expedited so that the resource and energy consumption for food processing can be significantly reduced. Bioactives and biopolymers extracted from food waste must be promoted, which will reduce the expense of fortified foods and increases the acceptance.

Future valorization techniques should be moulded in such a way that it should be economically feasible with less environmental impact. Some of the protocols used for food waste such as anaerobic digestion; well-crafted chemical techniques for separation; unified bio-conversion of base compounds to essential molecules and significant prototypes of biofuel; and advanced extraction techniques for recovering bioactive molecules have a less environmental impact with better economic benefits. However, most viable and revolutionary techniques can be developed only by joining the hands from various scientific disciplines. For the execution of these cutting-edge techniques to yield best results, there should be a strong alliance between the scientific community, industry and government. Efforts should be made from each sector in food production, processing, marketing and final consuming to minimize generating food waste. Governing bodies should monitories that industries are adopting novel technologies that reduce food waste and make aware consumers about the importance of using value-added products developed from food waste.

10. Conclusion

All these reports reviewed here suggested that food waste, whether plant-based or animal-based, they are abundant sources of bioactive molecules and biopolymers which can be effectively incorporated to develop functional foods, nutraceuticals, beauty care products and pharmaceuticals. They can also be used for wastewater treatment, biopackaging, biodiesel production, enzyme production and so many applications. Proper identification of waste sources and optimized extraction procedures will give a better yield of bioactives with economic importance, and this will reduce food waste. However,adequate awareness should be made among the people to reduce the food loses and food waste so that we can save the resources for the future generation.

references

Van-Thuoc et al. (2008), Wang et al. (2009), Zhang et al. (2007), Kumar and Kalita (2017)

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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