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Bioconversion of horticultural waste into value-added products: A Review

Aastha Dubey[1], Hari Shankar Gaur[1*], Uzma Manzoor[1], Shalini Singh[1], Prasun Kumar Singh[1], Chongtham Allaylay Devi[2], Jyoti Yadav[1], Mahima Choudhary[1] and Bulbul Ahmed[1]

[1]School of Agriculture, Galgotias University, Greater Noida, Uttar Pradesh -203201, India.

ABSTRACT

Horticultural crops are vital component of food diversity, human health, and agriculture, especially in India. These crops contribute greatly to the gross domestic product (GDP), provide employment, and support food and nutritional security. Fruit, vegetable and spice processing industries produce large volumes of solid by-products, including peels, pomace, seeds, cores, rinds, stones and spent residues, which constitute a significant proportion of the raw material processed. The magnitude of processing waste varies with commodity and technology, with fruit and vegetable processing generating approximately 30–60% solid residues, while spice oil and oleoresin industries produce exceptionally high waste fractions, reaching 80–90% of the processed material. At the global level, the fruit processing industry alone generates around 0.5 billion tonnes of processing waste annually, in addition to large volumes of wastewater, showing the resource-intensive nature of horticultural value addition. Improper management of these nutrient-rich but highly perishable processing residues leads to environmental problems like wastewater pollution, greenhouse gas emissions, odour formation and localized land and water contamination, while also imposing economic burdens on processors through disposal costs and inefficient resource utilization. These wastes could be gainfully utilized for production of animal feed, compost, biofertilizers, biofuels, essential oils, edible oils, food additives, pigments, nutraceuticals, preservatives, edible coatings, ethanol, and biodegradable plastics. Through appropriate bioconversion and value-addition technologies, horticultural residues can be transformed into a wide range of bio-based products, thereby minimizing environmental impacts and promoting resource efficiency. This review emphasizes the potential of utilizing horticultural waste to promote sustainable agricultural practices and support a circular economy.

Key words: Waste valorization, biotransformation, circular economy, sustainable gri-practices, value-added products.

INTRODUCTION

Horticultural crops include a wide range of fruits, vegetables, spices, medicinal plants, plantation crops etc. They are important for several reasons and play an important role in improving the variety of nutrients in our diet and provide essential nutrients that are vital for human health. India's horticultural sector plays a vital role in ensuring food and nutritional security. Horticultural crops contribute significantly to the country's Gross Domestic Product and provide employment opportunities thereby playing a pivotal role in Indian agricultural sector (Sah *et al.,* 122). The wide range of horticultural crops is grown in India because of its diverse agroclimatic conditions which make it conducive for cultivation (Priyadarshini *et al.*, 107). India contributes around 16% of the global vegetable production and 11% of global fruits production (Raj *et al.*, 110). The horticultural sector is rapidly expanding and gaining commercial importance (Sasikala, 125; Das, 28). The export potential of these crops further highlights their significance, offering higher returns for farmers and contributing to the national economy (Rabha, 109). Additionally, horticultural crops contribute to environmental sustainability. Perennial crops are noted for their carbon sequestration potential, which helps mitigate climate change impacts. Certain crops can be cultivated on less productive lands, enhancing soil health and biodiversity. This approach not only revitalizes underutilized area but also offers economic advantages through carbon credits, creating sustainable pathway for both environmental and financial benefits (Ganeshamurthy *et al.*, 37).

Along with the rapid expansion of horticultural production and value addition, large quantities of processing waste are generated during operations like washing, sorting, peeling, pulping, juice extraction and oleoresin recovery. Fruit and vegetable processing industries produce commodity-specific solid residues, including peels, pomace, seeds, cores, rinds and stones, which account for a substantial proportion of the raw material processed. Studies from Indian processing industries indicate that the magnitude of waste generation varies widely depending on the crop and processing method. For instance, mango processing discards nearly 60% of the fruit weight as peels and stones, whereas pineapple

*Corresponding author: harigaur@galgotiasuniversity.edu.in

[2]Amity Institute of Horticulture Studies and Research, Amity University, Noida, Uttar Pradesh, India

processing generates approximately 30% - 60% waste in the form of peel, core and trimmings (O'Shea *et al.*, 98; Varzakas *et al.*, 145). Similarly, the spice processing sector, particularly essential oil and oleoresin extraction, produces extremely high levels of solid residues, with 80% - 90% of the processed spice remaining as spent material after extraction (Sowbhagya, 137). At the global level, the fruit processing industry alone generates around 0.5 billion tonnes of processing waste annually, comprising solid residues such as peels, seeds and pomace, along with large volumes of wastewater (Argun *et al.*, 9). The sector is also highly water-intensive, with estimates indicating that nearly 10 L of wastewater are generated for every litre of fruit juice produced (Akbay *et al.*, 2).

Improper handling and disposal of horticultural processing waste pose serious environmental and economic challenges. Disposal through landfilling or incineration is considered inappropriate, as it leads to land and groundwater contamination, methane and carbon dioxide emissions, odour generation and secondary pollutants, particularly at the local and regional scale (Manhongo *et al.*, 81). Vegetable waste in developing nations is mostly produced during the stages of harvesting and processing, with only a small portion coming from consumption (Gustavsson *et al*., 47). Despite being rich in dietary fibre, bioactive compounds and valuable phytochemicals, these processing by-products are often discarded, resulting in inefficient utilization of critical resources such as land, water, fertilizers, energy and labour. Such losses translate into significant economic burdens across the horticultural value chain, affecting processors, farmers and consumers, while simultaneously increasing environmental pressure on ecosystems (Marcelli *et al.*, 82).

The utilization of horticultural wastes such as wastes of vegetables and other crop produce is one of the most effective strategies in the production of valuable products (Fig. 1). It has been evident that such wastes can be turned into products including; soil fertilizers, aquafeed meal, single cell protein, Organic carbons, essential oils, pigments, enzymes, edible coatings and fat substitutes (Reshmy *et al*., 114; Kumar *et al*., 67; Isidoro *et al*., 52; Hashempour-Baltork *et al*., 48). With proper practice of cultivation techniques and ideal bioconversion processes, these wastes can be transformed into bio-based products averting food wastage, boosting food adequacy and counteracting environmental effects. The conversion of waste to valuable resource helps apply sustainable practices in agriculture and industry hence circulation of the circular economy and resource efficiency principles. This review discusses about the extended use of horticultural waste in the production of several useful products.

Fig. 1: Valuable products derived from horticultural wastes.

Source: Author's compilation

PRODUCTION OF VALUE-ADDED PRODUCTS

Composting, Biofertilizer and Biofuel production

There are several viable possibilities of reusing horticultural waste like the peels of fruits and other livestock residues. This waste may further be utilized for generation of biofuels such as biohydrogen, biogas, bioethanol and biodiesel (Fig. 2). They originate from the fermented organic matter (Hoang *et al*., 49). Utilization of horticultural waste for bioenergy contributes to renewable energy usage as well as the reduction of the utilization of fossil fuel with a decline in greenhouse gas emissions. In the same way, mango peel and orange peel has also been used to prepare bacteria fermented bio ethanol which show that these wastes have got very good potential on producing bio fuels. In addition, Gosavi *et al*. (42) has established that biofuel can be produced as a result of the residue of this kind and as a result, waste can be dealt with effectively. Farm waste could also be utilized in the production of biofuel and other useful items through the solid-state fermentation as what was indicated by Sadh *et al*. (120). María *et al*. (83) also pointed out that microbial oil that is high in monounsaturated fatty acids, appropriate for biodiesel, can be obtained from rejected vegetable such as tomato, pepper, and watermelon (Table 1).

Additionally, horticultural waste can be transformed into biofertilizers through microbial

Table 1. Utilization of horticultural waste for composting, biofertilizer and biofuel production.

Source	Conversion approach	End Product(s)	Key outcome	References
Fruit peels and horticultural residues	Fermentation of organic matter	Biohydrogen, biogas, bioethanol, biodiesel	Renewable energy generation; reduced fossil fuel use and greenhouse gas emissions.	Hoang *et al*. (49)
Mango peel, orange peel	Bacteria-fermented process	Bioethanol	Demonstrated high potential of fruit peels for biofuel production.	Gosavi *et al*. (42)
Farm and horticultural waste	Solid-state fermentation	Biofuel and other useful products	Effective waste management and valorization.	Sadh *et al*. (120)
Tomato, pepper, watermelon	Microbial conversion	Microbial oil suitable for biodiesel	High monounsaturated fatty acid content suitable for biodiesel.	María *et al*. (83)
Horticultural waste	Microbial degradation	Biofertilizer	Reduced cellulose and lignin; promotion of plant growth.	Maurice (90)
Papaya, banana, watermelon waste	Solid-state fermentation	Biofertilizer	Improved plant growth and soil properties.	Lim and Matu (74)
Kitchen and horticultural waste	Enzymatic hydrolysis and fermentation	Biofertilizer formulations	Efficient nutrient recovery supporting zero-waste management.	Sharma *et al*. (129)
Horticultural waste	Composting	Compost	Enhanced crop yield and quality; nutrient-rich soil amendment.	Stoffella *et al*. (138)
Horticultural waste	Microbial processing	Biofuels and value-added products	Conversion of waste into value-added products.	Panda *et al*. (102)

degradation, which reduces cellulose and lignin content, while promoting plant growth (Maurice, 90). Biofertilizers made from horticultural waste provide sustainable alternatives to inorganic fertilizers, improving fertility of soil and promoting plant growth will lesser environmental impacts. Biofertilizers developed from several agro-waste like papaya, banana, watermelon etc, through solid state fermentation, has also shown promising results in improving plant growth and soil properties (Lim and Matu, 74). Innovative methods like the distinct hydrolysis and kitchen waste fermentation using multi-enzyme preparations have resulted in the production of efficient biofertilizer formulations, showcasing the potential for zero-waste management practices (Sharma *et al*., 129).

Composting horticultural waste not only prevents organic matter from ending up in landfills but also produces nutrient rice amendments for soil, thereby completing the organic waste management cycle. Stoffella *et al*. (138) discovered that compost from horticultural waste can enhance crop yield and quality. Similarly, Panda *et al*. (102) emphasized the potential of microbial processing to horticultural waste into value-added products like biofuels.

Thus, by integrating different approaches like biofuel production and composting for biofertilizer, horticultural waste can be effectively utilized to foster sustainable agriculture and energy production.

Animal feed

Using fruit and vegetables waste as animal feed provides a sustainable and economically feasible solution for waste management. These wastes offer valuable nutrients source for livestock, helping to bridge the gap between feed supply and demand (Patel *et al*., 103). Rich in bioactive compounds and nutrients, these wastes serve as cost-effective alternatives for livestock feed, reduce environmental pollution and improve farm profitability. By-products from the food industry are suitable for animal feed, both in terms of sanitation and nutritional value. Drying technologies like pulse combustion drying, microwaves and ovens have proven effective in preparing these wastes (Martin *et al*., 85). Crop wastes like cabbage leaves, peels of banana and vines of sweet potato, are utilized by urban and peri urban livestock producers. However, issues such as transportation costs and contamination need to be addressed (Katongole *et al*., 63). Additionally, the use of proteins derived from waste are being used in animal feed. It is an area of growing interest. Various agro-industrial wastes have been identified as potential plant protein supplements. These wastes can be processed to produce single-cell proteins, which have composition of amino acid similar to soy protein and can be efficiently applied to poultry, livestock and aquaculture rations (Wadhwa *et al*., 149). The conversion of horticultural waste into nutritious animal feed supports circular economy principles, promoting sustainability and resource efficiency within the agri-food sector (Table 2).

Essential oils

Successful extraction of essential oils from horticultural waste has been documented in a variety of studies. According to Din *et al*. (31) and Visakh *et al*. (147), essential oils extracted from *Citrus limon* and *C. maxima* peels have potent larvicidal and pest control properties. Because of their aromatic flavour, these oils derived from citrus peels are used not only as biopesticides but also in beverages, perfumes, and soaps. Additionally, Smeriglio *et al*. (135) found that the pruning waste of *Pistacia vera* and *Zingiber officinale* contains several bioactive compounds that have been identified for potential uses. Similarly, *Foeniculum vulgare* biomass waste was examined by Cautela *et al*. (21), who found that the essential oil contained a variety of bioactive substances like nerol and limonene, which add to the oil's unique flavour. According to Tavares *et al*. (142), steam distillation and hydro-distillation techniques are used to extract essential oils from the forest biomass waste of *Cupressus lusitanica* and *Cistus ladanifer*. It was found that these essential oils had antimicrobial qualities, especially against *Staphylococcus aureus* (Table 3).

Edible oils

The fruit seeds are a rich source of edible oils high in essential fatty acids. Seeds from mango, guava, passion fruit and rambutan contain considerable amounts of oil and beneficial fatty acids profile. Mango seed kernels, guava seeds, passion fruit seeds, and rambutan seeds contain significant oil percentages with beneficial fatty acid profiles. For example, rambutan seed fat has been identified as a potential substitute for cocoa butter in confectionery products (Issara *et al*., 53). Its fat consists of 36.8 - 42.0% oleic acid and 34.3 - 36.4% arachidic acid (Solıs-Fuentes *et al*., 136; Sirisompong *et al*., 134; Harahap *et al*.,

Table 2: Use of fruit and vegetable waste and related by-products as animal feed.

Waste source	Processing / preparation method	Nutritional / functional relevance	Reference
Fruit and vegetable waste	Direct utilization	Valuable nutrient source helping bridge feed supply-demand gap; cost-effective animal feed.	Patel *et al*. (103)
Food industry by-products	Drying (pulse combustion, microwave, oven drying)	Suitable in terms of sanitation and nutritional quality	Martin *et al*. (85)
Cabbage leaves, banana peels, sweet potato vines	Utilized by urban and peri-urban producers	Readily available feed resources for livestock	Katongole *et al*. (63)
Agro-industrial waste	Processing for protein recovery and single-cell protein production	Potential plant protein supplements with amino acid composition similar to soy protein; applicable in poultry, livestock and aquaculture rations	Wadhwa *et al*. (149)

Table 3: Essential oils derived from discarded horticultural crops.

Horticultural crops	Type of waste	Application	References
Citrus limon and *C. maxima*	Peel	Used as biopesticide as it possesses larvicidal and pest control properties. It is also used in beverages, perfumes, soaps, because of its aromatic flavour.	Din *et al*. (31) and Visakh *et al*. (147)
Zingiber officinale and *Pistacia vera*	Pruning waste	Their pruning waste consists of several bioactive compounds which were recognized.	Smeriglio *et al*. (135)
Foeniculum vulgare	Biomass waste	Analysis of waste revealed presence of many bioactive compounds in essential oil including limonene and nerol which contribute to distinctive flavour of oil.	Cautela *et al*. (21)
Cupressus lusitanica and *Cistus ladanifer*	Forest biomass waste	These are obtained via steam distillation and hydro distillation. These are known to show antimicrobial properties against *Staphylococcus aureus.*	Tavares *et al*. (142)

48; Yanty *et al*., 154). The use of rambutan seed oil in products of food and cosmetic can provide economic benefits. Passion fruit seed oil consists of unsaturated fatty acid (87.6 %). These include mainly linoleic (73.1 %) and oleic (13.8 %) acids (Malacrida and Jorge, 80). They can reduce free radicals activity. Guava seeds, discarded after making juice and pulp, have 5 - 13% oil and are abundant in fatty acids (Adsule and Kadam, 1). Similarly, pomegranate, cherry, and pumpkin seed oils are rich in bioactive components, they can be used in pharmaceutical, food and cosmetic products (Siano *et al*., 132). The seeds of some fruit species, including watermelon, grape, and apple contain high levels of phytosterols and unique fatty acids, with potential applications in biodiesel, cosmetic, and pharmaceutical industries (Górnaś and Rudzińska, 41). Banana peel consists of about 2.2–10.9% lipid. They are rich in polyunsaturated fatty acids like linoleic and α-linolenic acids (Emaga *et al*., 33). Such fatty acids prevent risk of cancer, cardiac diseases cancer and diabetes (Chahoud *et al*., 22). Dry tomato seeds consist of approximately 17% oil and have good amounts of oleic and linoleic acids. The major saturated fatty acids present are palmitic and stearic acids. Their fatty acid composition is similar to those of sunflower and soybean oils (Ryan *et al*., 118). Date pit oil protects the skin from ultraviolet sunlight. It has been used for the preparation of mayonnaise (Basuny and Al–Marzooq, 13) and has superior sensory characteristics compared to mayonnaise manufactured from corn oil (Table 4). These studies highlight the potential of fruit seed oils as a valuable and versatile resource.

Food Additives and preservatives

Numerous horticultural wastes have been investigated as potential sources of natural preservatives and food additives (Table 5). Unripe grapes can be used as a source of food additives, according to Wei *et al*. (151), as shown in Table 5. When added to beetroot puree, these additives were found to improve sensory qualities and optimize the advantages of polyphenols. Sun *et al*. (140) examined products made from mango seeds and documented their application as food preservatives. Mango seed methanolic extracts have been shown to enhance the quality of potato chips and ghee while inhibiting the oxidative deterioration of sunflower oil. Polyphenols extracted from unripe apple fruits can improve the

Table 4: Edible oils derived from horticultural residues.

Waste source	Type of residue	Oil content / major fatty acids	Functional properties /Applications	References
Mango, guava, passion fruit, rambutan	Seeds	Considerable oil content with beneficial fatty acid profile	Source of edible oils rich in essential fatty acids	Issara *et al*. (53)
Rambutan	Seed	Oleic acid (36.8–42.0%), arachidic acid (34.3–36.4%)	Potential substitute for cocoa butter; food and cosmetic applications	Solís-Fuentes *et al*. (136) and Sirisompong *et al*. (134)
Passion fruit	Seed	Unsaturated fatty acids (87.6%); linoleic (73.1%), oleic (13.8%)	Reduction of free radical activity; edible oil source	Malacrida and Jorge (80)
Guava	Seed	5–13% oil; rich in fatty acids	Utilized after juice and pulp processing; edible oil source	Adsule and Kadam (1)
Pomegranate, cherry, pumpkin	Seeds	Rich in bioactive components	Pharmaceutical, food and cosmetic applications	Siano *et al*. (132)
Watermelon, grape, apple	Seeds	High phytosterols and unique fatty acids	Potential use in biodiesel, cosmetic and pharmaceutical industries	Górnaś and Rudzińska (41)
Banana	Peel	Lipid content (2.2–10.9%); linoleic and α-linolenic acids	Prevention of cancer, cardiac diseases and diabetes	Emaga *et al*. (33); Chahoud *et al*. (22)
Tomato	Seed	17% oil; oleic and linoleic acids; palmitic and stearic acids	Fatty acid profile similar to sunflower and soybean oils	Ryan *et al*. (118)
Date	Pit (seed)	Oil with skin-protective properties	Used in mayonnaise; superior sensory quality compared to corn oil mayonnaise; UV protection	Basuny and Al-Marzooq (13)

Table 5: Food additives and preservatives derived from Horticultural wastes.

Horticultural crops	Type of waste	Product	Application	References
Unripe grapes	Fruit	Food additives	Enhance sensory characteristics and maximize the benefits of polyphenols in beetroot puree.	Wei *et al*. (151)
Mango	Seed	Food preservatives	Methanol from seed suppress oxidative deterioration of sunflower oil and improve the quality of ghee and potato chips	Sun *et al*. (140)
Apple	Unripe fruit	Food preservatives	Polyphenol may decrease the oxidative effects on sunflower oil and improve the quality of potato chips and ghee	Sun *et al*. (140)
Olive oil	Pomace	Food preservatives	Natural preservatives for food and medical applications.	Serra *et al*. (127)
Pomegranate, jackfruit and custard	Peels	Food preservatives	Exhibit antimicrobial activity because of the presence of compounds like furanone, furfural, and phenolics	Roy and Lingampeta (116)

quality of potato chips and ghee and reduce oxidative effects in sunflower oil (Sun *et al*., 140).

Additionally, olive oil pomace can be used as a source of natural food preservatives (Serra *et al*., 127). It was discovered that these preservatives could be used in the food and medical industries (Fig. 1). Furthermore, Roy and Lingampeta (116) found antimicrobial activity in pomegranate, jackfruit, and custard apple peels. Compounds like furanone, furfural and phenolic compounds were found to have antimicrobial qualities.

Pigments

As Table 6 summarizes, horticultural wastes have been investigated as potential sources of food coloring and natural pigments. According to Prodromidis *et al*. (108), green extraction techniques can be used to produce food coloring from onion leaf waste. Yoghurt products were successfully colored with the extracted polyphenols and colorants from solid onion discards. This method was emphasized as a viable substitute for artificial coloring agents. Kantifedaki *et al*. (60) investigated orange peel as a source of pigment. Solid-state, semi-solid-state and submerged fermentation methods were used to produce the pigments. According to the study, these pigments are used in a variety of industries, such as textiles, food coloring and cosmetics.

Nutraceuticals and Food supplements

As shown in Table 7, horticultural wastes have been widely studied for their nutraceutical composition and possible application in food supplements. According to Kumari *et al*. (69), the total phenolic content of apple seed waste ranges from 286.1 to 514.1 mg GAE 100 g^{-1} DM. Dihydrochalcones, hydroxycinnamic acid, hyperin, chlorogenic acid, quercetin, and protocatechuic acid are among the phenolic profile's constituents. Apple seeds also contained proteins in the range of 33.79–49.55 g, while antioxidant activity values ranged from 2.14–4.35 (DPPH) and 9.15–39.79 (ABTS). With phenolic compounds like gallic acid, protocatechuic acid, and chlorogenic acid (5-caffeoylquinic acid), apple peel has been demonstrated to have a high total phenolic content of 564 mg GAE 100 g^{-1} DM

Table 6: Value added products derived from horticultural wastes.

Horticultural crops	Type of waste	Product	Method used/ technology	Applications	References
Onion	Leaf waste	Food colorant	Green extraction	Utilizing the extracted polyphenols and colorants from solid discards of onion as food colorants in yoghurt product. This approach offers a as promising alternative to synthetic colouring agents	Prodromidis *et al*. (108)
Orange	Peel	Pigments	Solid state, semi-solid-state, and submerged fermentation	Applications in industries, like food colourants, cosmetics, and textiles.	Kantifedaki *et al*. (60)

Table 7: Phytochemical composition and nutraceutical potential of horticultural waste.

Horticultural crops	Type of waste	Total phenol	Phenol compounds	Total flavonoids	Organic acid	Proteins	Total dietary fibres (%)	Antioxidant activity		References
								DPPH	ABTS	
Apple	Seed	286.1–514.1	Dihydrochalcones, hydroxycinnamic acid, hyperin, chlorogenic acid, quercetin, protocatechuic acid,	-	-	33.79–49.55 g	-	2.14–4.35	9.15–39.79	Kumari *et al.* (69)
	Peel	564	Gallic acid, protocatechuic acid, chlorogenic acid (5-caffeoylquinic acid)	303	Citric Acid	25g	0.91	22 ± 0.00[a]	-	Matheus *et al.* (88)
	Pomace	348	Hydroxycinnamates, phloretin glycosides, quercetin glycosides, catechins, procyanidins	40.91 ± 0.53	Citric Acid	4.45 g	88.5	72.6 ± 1.6[a]	84.3 ± 1.6[a]	Kumar et al. (65);
Banana	Peel	1500.2	Carotenoids (palmitate or laurate, xanthophylls, caprate, xanthophyll)	900.3	Citric Acid	6.02 g	50	IC_{50}: 55.23[b]	-	Behiry *et al.* (15)
Mango	Seed	ca. 1920	Mangiferin, hesperidin, vanillin, glucoside, quercetin, kaempferol	ca. 290	-	6–13%	51.2	ca. 90 mg TE g−1 DM	-	Bernal-Mercado *et al.* (16)
	Peel	4500	Flavonol glycosides	-	Lactic acid	9.5 g	-	22.4 ± 0.07	ca. 620 mg TE g−1 DM	Baddi *et al.* (11)
	Pulp	100	-	28.2	-	-	20.9	-	-	Sudha *et al.* (139)
Carrot	Pomace	ca. 500	Carotene (α and β)	ca. 320	succinic acid, α-ketoglutaric acid, lactic acid	10.06 g	63.6	35 mg TE g−1 DM	-	Gulsunoglu *et al.* (45)
Tomato	Pomace	86.5	Lycopene	-	Lactic acid	17 to 22 g	50	-	-	Nour *et al.* (96)
Potato	Peel	-	Gallic, protocatechuic, Chlorogenic, and caffeic acids, isomer II, chlorogenic acid	-	Lactic acid	10.6 ± 0.2 g/100 g of DW and 1.80 ± 0.03 g/100 g	5.6	-	-	Zhang *et al.* (156)

[a: (μg mL−1) at 50% scavenging of DPPH radical; b: Percentage of DPPH or ABTS radical inhibition; DPPH: 2,2-diphenyl-1-picrylhydrazyl; ABTS: 2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid); IC50: median inhibition concentration; GAE: gallic acid equivalent]; Total Phenol measured in mg GAE 100 g−1 DM; Total Flavonoids measured in mg QE 100 g−1 DM; DPPH measured in mmol TE 100 g−1 DM; ABTS measured in mmol TE 100 g−1 and the total flavonoid content was 303 mg QE 100 g^{-1} DM. According to Matheus *et al*. (88), apple peel also had a protein content of 25 g, dietary fiber content of 0.91%, antioxidant activity of 22 ± 0.00 (DPPH), and citric acid as the main organic acid. Kumar *et al*. (65) reported that apple pomace has a total phenolic content of 348 mg GAE 100 g^{-1} DM. The main phenolic constituents are hydroxycinnamates, phloretin glycosides, quercetin glycosides, catechins, and procyanidins. 40.91 ± 0.53 mg QE 100 g^{-1} DM was the total flavonoid content. Along with 4.45 g of protein and 88.5% of dietary fiber, citric acid was found to be the organic acid and antioxidant activity values of 72.6 ± 1.6 (DPPH) and 84.3 ± 1.6 (ABTS). According to Behiry *et al*. (15), banana peels have a high total phenolic content of 1500.2 mg GAE 100 g^{-1} DM. The main compounds found in banana peels are carotenoids like palmitate or laurate, xanthophylls, and caprate. Citric acid was the most common organic acid, and the total flavonoid content was 900.3 mg QE 100 g^{-1} DM and banana peel had an IC^2_0 value of 55.23 for antioxidant activity, 6.02 g of protein, and 50% dietary fiber.

Edible coatings/films

Table 8 illustrates how various horticultural wastes have been used to develop edible coatings and films for food preservation and related uses. An edible coating made from apple peel was used on beef patties (Shin *et al*., 131). It was discovered that the coating effectively improved product stability by suppressing microbial growth and inhibiting lipid oxidation.

Similarly, Moghadam *et al*. (94) employed pomegranate peel to develop edible coatings that were utilized in the food industry to create edible films meant for packaging. According to Al-Anbari *et al*. (3), cupcakes were coated with an edible substance made from orange peel.

Edible films have also been made using banana peels. Edible films made from banana peels were found to be useful in wound bacteriostasis because they prevented the growth of Escherichia coli and Staphylococcus aureus (Franco *et al*., 35). In another study, Simonetti *et al*. (133) described the application of edible coatings made from unripe grape fruit that effectively inhibited the fungal activity of different dermatophytes. Furthermore, Liu *et al*. (75) found that edible coatings made from asparagus waste were successful in extending the shelf life and maintaining the quality of strawberry fruit.

Ethanol production

Geng *et al*. (38) demonstrated that a modified organosolv method is effective for pre-treating horticultural waste for ethanol production. Similarly, Gonçalves *et al*. (40) highlighted the possibility of using horticultural wastes and municipal wastes, for cellulosic ethanol production. Matsakas *et al*. (89) and Karimi and Karimi (62) investigated the household food waste utilization, for ethanol production. Matsakas *et al*. (89) noted the advantages of a separate liquefaction or saccharification process while Karimi and Karimi (62) achieved effective ethanol production from waste of kitchen. Numerous studies have shown that horticultural wastes can serve as good source of ethanol production (Table 9). Waghmare *et al*. (150) identified unripe banana peels as a good feedstock, with Waghmare *et al*. (150) achieving an ethanol yield of 35.5 g/L. Guerrero *et al*. (44) explored banana and Citrus peel wastes for second generation ethanol production. A study revealed that

Table 8. Edible coatings derived from different horticultural wastes.

Horticultural crops	Type of waste	Product	Applications	References
Apple	Peel	Edible coating	Used on beef patties as coating to inhibit lipid oxidation and microbes' growth.	Shin *et al*. (131)
Pomegranate	Peel	Edible coating	Used in food industry to manufacture edible films for packaging.	Moghadam *et al*. (94)
Orange	Peel	Edible coating	Applied on cupcake	Al-Anbari *et al*. (3)
Banana	Peel	Edible film	Application in wound bacteriostasis as these are known found to inhibit *Staphylococcus aureus* and *Escherichia coli*	Franco *et al*. (35)
Grapes	Unripe fruit	Edible coating	Inhibit the fungal activity of various dermatophytes	Simonetti *et al*. (133)
Asparagus waste	-	Edible coating	Effectively preserve strawberry fruit quality and extend shelf life	Liu *et al*. (75)

Table 9. Ethanol production from horticultural wastes.

Waste source / substrate	Processing / approach	Key outcome	Reference
Horticultural waste	Modified organosolv pretreatment	Effective pretreatment method for ethanol production	Geng *et al.* (38)
Horticultural and municipal waste	Cellulosic ethanol production	Demonstrated feasibility of ethanol production from mixed wastes	Gonçalves *et al.* (40)
Kitchen waste	Liquefaction / saccharification	Separate liquefaction or saccharification improved ethanol production	Matsakas *et al.* (89)
Kitchen waste	Fermentation-based ethanol production	Achieved effective ethanol production from kitchen waste	Karimi and Karimi (62)
Banana peel (unripe)	Fermentation	Identified as a good feedstock for ethanol production (35.5 g L^{-1} yield)	Waghmare *et al.* (150)
Banana peel and citrus peel	Second-generation ethanol production	Demonstrated suitability of peels for ethanol production	Guerrero *et al.* (44)
Mandarin, orange and lemon peels	Fermentation	Mandarin peel yielded higher ethanol than orange and lemon peels	Pilco *et al.* (105)
Potato peel, banana peel, apple pomace, beet waste, citrus waste	Fermentation of structural carbohydrates	Identified as promising substrates due to pectin, hemicellulose and cellulose content	Khandaker *et al.* (64);
Pineapple	Fermentation	Rich in sucrose, starch and hemicellulose, suitable for ethanol production	Sarkar *et al.* (124)

as compared to peels of orange and lemon, mandarin gave highest ethanol production (Pilco *et al*., 105). Horticultural wastes, like peel of potato and banana apple pomace, beet waste, and citrus waste, have been identified as promising substrates for bioethanol production (Sarkar *et al*., 124; Khandaker *et al*., 64; Pilco *et al*., 105). These wastes are source of pectin, hemicellulose and cellulose which are good for fermentation (Sarkar *et al*., 124). Pineapple is rich in sucrose, starch, and hemicellulose, hence one of the sources of bioethanol (Sarkar *et al.,* 124; Khandaker *et al*., 64).

Industrial materials

Table 10 summarizes the transformation of horticultural wastes into materials that are useful for industry. According to Shanmugavadivu *et al*. (128), pomegranate peel waste was used to develop nanoparticles with sizes ranging from 5 to 50 nm. These nanoparticles demonstrated antimicrobial

Table 10. Nanoparticles derived from horticultural wastes.

Horticultural crops	Type of waste	Product	Applications	References
Pomegranate	Peel	Nanoparticles (5–50 nm)	Antibacterial activity against *S. aureus and E. coli.*	Shanmugavadivu *et al*. (128)
		Nanoparticles (20–40 nm)	Antibacterial activity against *E. coli*, *Staphylococcus epidermidis*, *and* Cytotoxicity against human colon cancer cell line.	Devanesan *et al*. (30)
Banana	Peel	Nanoparticles	Antibacterial activity against *P. aeruginosa*, *E. coli, Bacillus subtilis*	Ibrahim (51)
Citrus	Peel and pomace	Bacterial Cellulose	Waste recycling	Fan *et al*. (34)
Potato	Processing waste	Polyhydroxybutyrate	Converted into a concentrated glucose solution for PHB production	Rusendi and Sheppard (117)
Coconut	Husks	Fiberboards	Produced high-strength, high-density fiberboards from unripe coconut husks	Junior *et al*. (58)

activity against *Escherichia coli* and *Staphylococcus aureus*. Similarly, Devanesan *et al*. (30) developed 20–40 nm-sized pomegranate peel nanoparticles that demonstrated both cytotoxic and antibacterial activity against a human colon cancer cell line and E. coli and Staphylococcus epidermidis. The synthesis of nanoparticles from banana peels has also been investigated. According to Ibrahim (51), nanoparticles made from banana peels showed antibacterial activity against *Bacillus subtilis*, *Escherichia coli* and *Pseudomonas aeruginosa*.

Horticultural wastes have been used to produce biopolymers in addition to nanoparticles. The production of bacterial cellulose from citrus peel and pomace was reported by Fan *et al*. (34), emphasizing its use in waste recycling. Additionally, Rusendi and Sheppard (117) showed that waste from potato processing can be transformed into a concentrated glucose solution, which acts as a substrate for the production of polyhydroxybutyrate (PHB). Composite materials have also been developed using horticultural residues. According to Junior *et al*. (58), fiberboards made from unripe coconut husks have high strength and density.

Other products

Cosmetics: Table 11 summarizes the use of horticultural wastes in the production of cosmetic products. According to Kar (61), pomegranate peel can be pyrolyzed to produce bio-oil at temperatures between 400 and 550 °C with a heating rate of 10 °C min^{-1}. Due to the presence of compounds like phenols, furfural, and their derivatives, the resulting bio-oil contained fine chemicals, suggesting its potential relevance for cosmetic and related applications. Pomegranate seed extract was used in another study by Bogdan *et al*. (17) to develop a cosmetic cream. Pomegranate seed extract and *Croton lechleri* resin extract were combined in the formulation. According to the study, this cream may help control skin changes brought on by stretch marks. Additionally, waste derived from date has been investigated for use in cosmetics. According to Alharbi *et al*. (4), date extract and seed oil are used in cosmetic products (Fig. 2). These products demonstrated the potential of date by-products in skincare formulations by effectively reducing acne, melanin, and eczema. Similarly, Nunes *et al*. (97) found that cosmetics made from leftovers from grape processing. These products' antioxidant and anti-wrinkle qualities support their use in cosmetic applications.

Flour: There have been a number of studies on the use of flour for human food from horticultural waste. Melissa *et al.* (92) made flour out of plantain and banana peels that passed quality standards. Marques *et al*. (84) conducted tests with barbados cherry waste flour, a source of fiber and bioactive compounds in meat products and bakery. Similarly, Costa *et al*. (26), showed that beetroot waste with

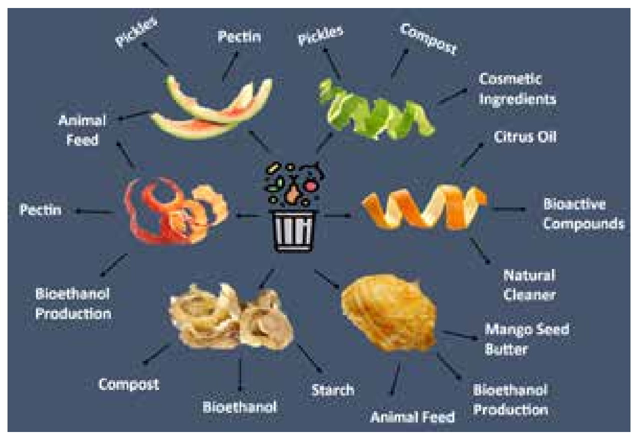

Fig. 2: Innovative products derived from different parts of fruits and vegetables waste.

Picture source: Author's Compilation

Table 11. Cosmetic products derived from different horticultural wastes.

Horticultural crops	Type of waste	Product	Method used/ technology	Applications	References
Pomegranate	Peel	Bio - oil	Pyrolysis at 400 to 550°C for 10°C/ min.	It produces fine chemicals because of the presence of compounds like phenols, furfural, and its derivatives in the oil	Kar (61)
	Seed	Cosmetic cream	Croton lechleri resin extract was used in combination	This cream could be beneficial in managing skin changes associated with stretch marks.	Bogdan *et al.* (17)
Date	Extract and seed oil	Cosmetic product	-	Reduce eczema, melanin, and acne	Alharbi *et al*. (4)
Grapes	Processing by-products	Cosmetic product	-	Antiwrinkle, and antioxidant properties	Nunes et al. (97)

less processing was turned into flour with significant antioxidant activity and betalain content. These studies highlight the use of horticulture waste as a potential source for functional and nutritious flour.

Other innovative products from horticultural wastes

Table 12 lists a few innovative uses for horticultural waste that go beyond traditional food and feed applications. For example, biochar made from pomegranate peels and pyrolyzed at 300 °C has demonstrated a strong capacity for copper (II) adsorption, suggesting its potential use in environmental remediation. Similarly, onion peel-based composite films have been investigated for use in food packaging, where they improve packaging performance by providing UV protection and antioxidant functionality (Barbosa *et al*. 12). Another example is the use of carbon dots made from banana peels and synthesized with the aid of microwaves. These dots have been used to determine colitoxin DNA, indicating their applicability in biosensing applications (Huang *et al*. 50). Additionally, pH indicator films that show discernible color changes in response to pH variation have been developed using pomace extracts from blueberries and blackberries, making them appropriate for real-time food spoilage monitorin (Luchese 77)g. Together, these examples show how horticultural wastes can be converted into valuable materials with uses in the fields of food safety, packaging, sensing, and the environment.

Table 12. Innovative products derived from different horticultural wastes.

Commodity	Type of waste	Product	Method used/ technology	Applications	References
Pomegranate	Peel	Biochar	Pyrolysis at 300 °C for 2 h	Adsorption of Copper (II) was 52 mg/g	Cao *et al*. (20)
Onion	Peel	Food packaging film	-	Application of onion composite films for food packaging, enhancing UV protection and antioxidant properties.	Barbosa *et al*. (12)
Orange; potato; drum stick	Peel	Microbiological media.	-	Growth analysis of Trichoderma sp., Aspergillus sp.	Kadam *et al*. (59)
Banana	Peel	Carbon dots	Microwave-assisted/500 W/20 min	Determination of colitoxin DNA	Huang *et al*. (50)
Orange	Peel	Edible and healthy snack	Direct ink writing (DIW) 3D printing	Using 3D printing to transform orange peel waste into edible snacks, improving the nutritional value and ensuring non-toxicity of the product.	Tan *et al*. (141)
	Whole fruit	Modification of waste to sponge-like material	esterification with maleic anhydride	Utilize as a filler in bio composites	Bátori *et al*. (14)
Pomegranate	Peel	Carbon dots	hydrothermal carbonization	Recovery of latent prints	Yadav *et al*. (153)
Melon	Fruit waste	Aromatherapy candles		Grade D melons such as Melon Golden Langkawi, can be used in making aromatherapy candles along with other products including Palm Wax, Essence Oil Melon, and Liquid Colour Candle	Ambarkahi *et al*. (6)
Blueberry and blackberry	Pomace extracts	pH indicator film		These films exhibited visible colour changes in response to pH variations, making them suitable for monitoring food spoilage.	Luchese (77); Luchese (78); Kurek (70); Kurek (71)

Conclusion and future prospectives

The use of horticultural waste offers a pivotal opportunity to improve agricultural sustainability addressing food security, economic viability and environmental protection. This review underscores the importance of horticulture waste utilization in the forms of animal feed, composts, biofertilizers, biofuels and many higher value-added products which includes essential oils, edible coatings and biodegradable plastics. Waste management has to be efficient in a country like India, which is poised towards a circular economy aimed at resource efficiency and sustainable development.

Many major areas of horticultural waste management require further research and development to unlock the true potential of horticultural waste utilization. Among other areas, biotechnological processes can be made more efficient and yield better conversion efficiencies with higher-value end-products from horticultural wastes.

It is important to evaluate the economic feasibility of horticultural waste-based products as well as identify markets for these products. Through policies and incentives that promote commercialization of waste derived products, investments are attracted while stakeholders adopt them.

In conclusion, horticultural waste has multiple uses whose potential could revolutionize agricultural sustainability, economic resilience and environmental health. If more research would be done in this area, then instead of being a liability it might end up becoming a useful resource contributing to an economically prosperous and more sustainable future for horticulture and humanity

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