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REVIEW ARTICLE

Turning trash into treasure: Valorization of fruit waste for sustainable bioeconomy

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Abstract

The effective utilization of fruit waste offers a significant opportunity to advance sustainable resource management and reduce environmental burdens. This comprehensive overview brings together current research on the diverse applications of fruit by-products, showcasing their potential across various industries. Fruit waste, comprising peels, seeds and pulp, is highly valuable to the food, pharmaceutical and cosmetic industries due to its rich content of bioactive compounds such as vitamins, fibre and antioxidants. In addition to industrial applications, the integration of fruit waste into agricultural practices, such as compost or biofertilizer, improves soil health and enhances crop productivity. These organic amendments reduce dependence on synthetic inputs and promote environmentally responsible farming practices. Beyond agriculture and industry, fruit waste is increasingly explored for its role in sustainable material and energy development. Notably, its high carbohydrate and cellulose content make it suitable for biofuel production, while its film-forming properties support the creation of biodegradable packaging as a replacement for plastics. Furthermore, processed fruit residues are proving to be effective animal feed components, offering nutritional benefits and lowering feed costs in livestock production. This review stresses the economic and environmental advantages of fruit waste utilization and urges the development of scalable, cost-effective processing technologies to maximize its potential. It underscores the importance of ongoing research and cross-sector collaboration among academia, industry and policymakers to unlock the full value of fruit by-products. Such efforts are essential to advancing circular economy principles and reducing the environmental impact of food production systems.

Keywords: agricultural benefits; economic and environmental impact; innovative products; nutrient-rich by-products; sustainable use of fruit waste

Introduction

A significant proportion, ranging from 25-50 % of fruits and vegetables produced globally is lost along the supply chain from farm to table, a phenomenon widely recognized as post-harvest loss (1). Transport and handling account for approximately 25-30 % of these losses. The fruit juice industry produces 5.5 million tonnes (Mt) of waste, with 20-30 % treated (2). These losses vary by crop, with waste percentages differing for various fruits as detailed in Table 1.

Table 1. Different types of fruit wastage and their percentage losses

Fruits	Type of waste	Percentage of losses (%)	References
Mango	Seed, peel	25.51	(3)
Banana	Peel	26.5	(4)
Pineapple	Peel	32.12	(5)
Grapes	Stem, seeds, skin	53.00	(6)
Orange	Peel, seeds	29.00	(7)

Fruit by-products like peels, seeds and pomace contribute significantly to municipal solid waste. Peels and seeds are often discarded during processing despite their nutritional value, while pomace remains a major by-product of the juice industry (8). Fruit waste, rich in protein, sugars and minerals, can address feed scarcity in developing countries. It may be fed directly or processed through drying and ensiling (9). Additionally, its phytochemicals, fibers and vitamins make it a nutritious alternative to conventional feed ingredients. Using fruit waste in dairy cow diets enhances milk's fatty acid content without reducing production.

Different wastages in fruit crops

Mango

Mango processing generates significant waste, mainly peels and seeds (10). Its peel makes up 15-20 % of the fruit's weight and seeds 20-60 %, depending on the variety (11-13). Mango peel is rich in bioactive compounds like dietary fiber, vitamins C and E, carotenoids and flavonoids, making it a potential functional food (14). It is also a valuable source of aromatic compounds for flavoring and volatile compound extraction (15).

Gallate and penta-O-galloylglucoside from mango exhibit antioxidant, anti-tumor and antimicrobial properties, highlighting their pharmaceutical potential (16). Mango seed kernels, though low in protein, contain essential amino acids like leucine and lysine (17). Mango peel pectin has superior gelling properties, while its flour is used in various food products, including bread, cookies and jams (16). Additionally, *Pichia pinus* yeast is employed to produce lactic acid and single -cell proteins from mango peel.

Banana

Banana processing generates significant waste, with peels accounting for 40 % of the fruit's weight (18). Banana cultivation also yields large amounts of biomass, with pseudo-stems and peduncles being valuable fiber sources. These fibers are used in industries for paper, cardboard, tea bags, currency notes and polymer composites (19). Rich in cellulose and fiber, banana peels are increasingly studied for their potential use as an alternative flour source, adding value to this by-product (20). Plantain roots and stems are traditionally used to bind leaves that serve as baskets, mats and natural packaging materials (21). Old leaves serve as bunch covers, large leaves as umbrellas and dried leaves as fuel for oyster mushroom cultivation.

Pineapple

Pineapple processing generates by-products like peel and core, rich in fibers, pectins, sugars, proteins, vitamins, minerals and phenolic compounds such as ferulic acid and catechin (22, 23). Pineapple peel contains 6.5-35 % hemicellulose, 12-50 % cellulose and 5-30 % lignin, while the core has 41.1-43.5 % cellulose, 5.78 % lignin and 28.5 % hemicellulose (24). The crown has 67.1-85 % cellulose, 13.8 % lignin and 21-21.8 % hemicellulose. These by-products are being explored for eco-friendly biodiesel production, offering economic and environmental benefits.

Citrus

Citrus processing produces various wastes, including solid waste (peels, seeds, rags) and liquid waste (wash water, can cooler overflows and effluents) (25). Citrus peel, a byproduct of juice production, is rich in phenols and flavonoids with antioxidant and health benefits, but lacks commercial value. This study focuses on citrus extracts, particularly Eco-enzyme, known for its phenolic compounds and biological effects (26). Orange peel essential oils mainly consist of limonene (94 %), with smaller amounts of myrcene, linalool and other compounds. Limonene is known for its insecticidal properties (27). Citrus seed processing yields oil (20-40 % of seed weight) and seed meal, with the oil being rich in unsaturated fatty acids, especially linoleic acid, along with oleic, stearic, palmitic and α-linolenic acids (28).

Jackfruit

Jackfruit waste includes unused peels and seeds, which are rich in pectin, fiber and starch (29, 30). While edible, jackfruit seeds have a short shelf life, but drying them deactivates antinutritional compounds, making them suitable for flour production.

Apple

Apple pomace, a byproduct of apple processing, is rich in carbohydrates, fiber, vitamins and antioxidants, with polyphenols concentrated in the peels (9). It contains 10-15 % pectin and significant amounts of insoluble and soluble fiber (31). Additionally, waste from apple orchards, including leaves and branches, can be processed into biofuels like hydrogen, ethanol and methane (32).

Degradable packaging materials

The increased use of plastic has harmed the environment and animal welfare (33). Developing biodegradable packaging from renewable sources like starch, cellulose and pectin derived from fruit peels and seeds is essential for replacing plastic materials (34).

Biodegradable packaging research can be categorized into four types: 1) Anti-corrosive for durable metals, 2) Pharmaceutical for packaging medical items, 3) Electronic packaging for protecting components and 4) Food packaging to prevent contamination and extend shelf life (35).

Fruit processing byproducts contain carbohydrates such as cellulose and starch, which can replace traditional starches in films and coatings (36).

Mango

Mangoes are rich in pectin, a natural gelling agent (37). Plasticizers like glycerol, sorbitol and polyethylene glycol enhance flexibility and permeability by disrupting polymer hydrogen bonds (38). Sorbitol improves film strength and elasticity (39). Nayak and Rayaguru's method for extracting starch from mango seed kernels involved washing, slicing, peeling and sun-drying the kernels, followed by oven drying at 105 °C. The dried kernels were ground and soaked in sulfur dioxide for four days at varying mass-to-liquid ratios (1:5, 1:10, 1:15, 1:20), with starch yield depending on the ratio and soaking time (40). Mango Kernel Flour (MKF)/glycerol films were prepared by mixing distilled water with 5 % w/w MKF, heating to 90 °C and stirring for 30 min. Glycerol (50 % w/w of MKF) was added, followed by further stirring. The mixture was sonicated to remove bubbles and poured into Petri plates to dry for 48 hrs (41).

Banana

Banana pseudo-stems are rich in cellulose fibers (42), yet remain underutilized. One innovative application involves the use of the ionic liquid 1-allyl-3-methylimidazolium chloride ([AMIm][Cl]) along with delignified fibers to create regenerated cellulose films for sustainable mango packaging (43). Additionally, banana peel fibers, often from food industry waste, offer a sustainable alternative to polyethylene or polystyrene (44). Banana peels are soaked in 0.2 M sodium metabisulfite solution for 45 min to act as a preservative and antioxidant (45). After boiling for 30 min, the peels are drained, dried and blended into a paste. To prepare filmogenic suspensions, banana peel flour, cornstarch and water were heated to 90 °C, stirred and homogenized. Glycerol was added and the mixture was stirred further before filtering and pouring into Petri dishes to form starch banana peel film (46).

Citrus

Orange peels, rich in starch and pectin, hold potential for bioplastic production due to their strength-enhancing properties (47). Limonene in the peels can be oxidized with CO_2 to create bioplastics, but industrial use remains limited (48). Sweet orange peel was washed, sun-dried for 20 hrs, oven-dried at 60 °C for 18 hrs and ground into fine powder (100 µm) before storage at room temperature (49). PVA dissolved in hot water was heated to 90 °C and stirred for 2 hrs. OPP (5-20 %) was added, stirred further and the mixture was poured onto a glass plate to set before removing the film. (50-52).

Jackfruit

Starch, a cheap and renewable resource, is widely used for biodegradable films (48). Using jackfruit seed starch for bioplastics can help reduce waste from the jackfruit seed (53). Jackfruit seeds were cleaned, cubed and blended with water. The slurry was filtered and the starch was separated after settling for 24 hrs. The wet starch was oven-dried at 65 °C for 12 hrs, ground and sifted into a fine powder (54). Jackfruit starch solution was stirred for 24 hrs, gelatinized at 95 °C and mixed with glycerol and anthocyanin. The solution was poured onto a Mylar plate, spread evenly and dried at 30 °C for 24 hrs (55) .

Apple

Red apple pomace, comprising 25-30 % of raw apples, is rich in phenolic compounds. PVA films with apple pomace exhibit antioxidant properties, but whole pomace reduces tensile strength and elongation (56). Apple peels were washed, sun-dried, ground and sieved (60-mesh) to obtain a fine powder, which was then stored in an airtight container. Apple peel-based edible films were made using high-pressure homogenization. Increasing glycerol concentration (23-44 %) reduced moisture content and improved barrier properties, making them suitable for food wrapping.

Animal feed in agriculture

Mango

Mango peels, rich in sugars (13.2 %), are energy-rich feed but unsuitable for ruminants due to high moisture and acidity. Adding nitrogen or protein improves energy utilization and a mixture of rice straw and beans promotes fermentation for palatable silage (57). Incorporating Leucaena leaves into mango peel silage with rice straw improved digestibility to 60 % (58). Substituting maize bran with up to 37.5 % processed mango fruit boosted sheep growth without affecting welfare (59).

Banana

Goats, dairy cattle, beef cattle and rabbits readily consume banana waste due to its digestibility (60–63). Calves fed banana waste showed improved growth (62), Dairy cows fed banana peels increased milk production. Dried, ripe plantain peels replace corn for goats, while dried banana peels can be fed to pigs up to 20 % without affecting growth (64).

Pineapple

Pineapple juice extraction produces waste (peels, pomace, crowns), accounting for 33 % of processing by-products (64). Raw pineapple waste is high in dry matter and fiber but low in minerals, containing soluble sugars, crude protein and pectin (65). Silage with pineapple waste and chicken litter reduces feed costs and pineapple waste can replace up to 50 % of roughage in dairy calf feed without affecting milk production (66). Anaerobic digestion slurry can be used as animal feed (67).

Citrus

Pigs can consume up to 5 % dried citrus pulp and fresh pulp should be mixed with hay or straw for better ensiling. Cattle enjoy ensiled orange pulp, which improves silage quality (64). Citrus pulp, mixed with straw, creates high-quality silage and helps buffer rumen pH due to its high fiber. It is a safer feed alternative to grain for dairy cows on high-concentrate diets (68).

Apple

Apple pomace is a valuable feed for calves and provides 1.86 Mcal of metabolizable energy per kg of dry matter for lactating dairy cows (69). Holstein cows fed 15 % ensiled apple pomace showed improved milk yield and composition (70).

Biofuel production: Fruit wastes, rich in sugars and carbohydrates, can be used for bioethanol production through enzymatic hydrolysis with xylanase and cellulase enzymes. Pineapples and bananas are effective sources and cleaning fruit wastes with water and steam, followed by fermentation with *Saccharomyces cerevisiae,* produces bioethanol (71). Fermenting apple pomace and overripe bananas with baker's yeast can yield alcohol concentrations of 48 % after distillation (72) .

Bioethanol can be produced from pineapple and jackfruit waste through acid hydrolysis and fermentation with *Saccharomyces cerevisiae*, yielding 0.090 % ethanol from pineapple and 0.045 % from jackfruit (73). Orange and mango peels can also be fermented with bacterial strains like *Enterobacter cloacae*, *Pseudomonas aeruginosa* and *Bacillus cereus* to produce ethanol (74).

Banana peels, with high cellulose and low lignin, are ideal for bioethanol production. Ethanol yield depends on pH, typically around 4.5 to 5.5 for maximum enzyme activity during hydrolysis (75). Fruit wastes like bananas, apples and pomegranates can also serve as substrates, reducing bioethanol production costs. Converting daily household waste into ethanol offers a promising solution.

Conclusion

Fruit waste holds immense potential for contributing to sustainable practices across multiple sectors. Rich in bioactive compounds, fibers and nutrients, these by-products can be efficiently transformed into high value outputs such as biofertilizers, biodegradable packaging, biofuels, these by-products can be efficiently transformed into high value outputs and animal feed. This review emphasizes the need for innovative processing techniques and collaborative efforts to maximize the value of fruit by-products. Adopting these strategies supports a circular economy, minimizes environmental impact and promotes sustainable development.

Authors' contributions

DP and PSK prepared the original draft. KSVS, IM, VVAG and RG corrected and edited the manuscript.

Compliance with ethical standards

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