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Review Article

Waste to Worth: A Comprehensive Review on Potential Applications of Residual Biomass from Fruits and Vegetables

Naseem Zahra[1]*, Muhammad Khalid Saeed[1], Sabeen Razzaq[2] and Farwa Shabeer[2]

[1]*Food and Biotechnology research Center, Pakistan Council of Scientific and Industrial Research Laboratories Complex Lahore, Pakistan*

[2]*Department of Biochemistry and Molecular Biology, The Islamia University of Bahawalpur, Bahawalpur, Pakistan*

***Corresponding Author:** Naseem Zahra, Food and Biotechnology research Center, Pakistan Council of Scientific and Industrial Research Laboratories Complex Lahore, Pakistan.

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Abstract

Although fruits and vegetables are vital components of balanced diet, they also contribute significantly to global food waste. A substantial portion of this waste include residual biomasses such as peels, seeds, pomace, trimmings and leaves, which are rich in bioactive compounds like vitamins, minerals, dietary fibers, and phytochemicals. This review highlights the potential of utilizing these residues for the development of value-added products, thereby contributing to environmental pollution reduction and sustainable bioeconomy. This review also focuses potential applications of fruits and vegetables wastes across multiple industries i.e. food and nutraceuticals, cosmetics and personal care, pharmaceutical, biodegradable packaging and bioplastics and textile and dyeing industries, supported by real-world examples. Various case studies and recent advancements in this domain are discussed to illustrate practical approaches for fruit and vegetable waste valorization. The findings indicate that, when processed through efficient bioconversion pathways, these wastes can be transformed into economically and nutritionally valuable resources. However, in developing countries like Pakistan, a lack of regulatory policies and structured framework remains a major barrier to implementation.

Keywords: *Residual Biomass; Bioactive Compounds; Sustainable Bioeconomy; Nutraceuticals; Bioplastics; Waste Valorization; Bioconversion*

Introduction

Fruits and vegetables are key constituents of balanced diet as they provide essential nutrients i.e. vitamins (A, C, E), minerals (potassium, magnesium), dietary fibers, antioxidants, and many phytochemicals. These nutrients assure normal functioning of body such as to boost immunity and to support normal digestion and also provide protection against chronic diseases like cardiovascular diseases [1]. The Food and Agriculture Organization (FAO) reported a dramatic expansion in fruit and vegetable production, with production increasing to more than 2.3 billion tonnes annually worldwide [2].

Regardless of their nutritional importance, they constitute a major portion of global food waste, with approximately 45% of fruits and vegetables being wasted throughout the supply chain [3].

In 2022, global food waste from retail, food service, and household sectors was estimated at approximately 1.05 billion tonnes corresponding to an average of 132 kg per capita annually. Of this waste, household level accounted for 79kg per capita per year (UNEP, 2024).

This waste mainly consists of peels, pulps, seeds, and skins which are not only biodegradable but also contain essential nutrients such as carotenoids, dietary fibers, polyphenols, and natural pigments [4,5].

The waste is often referred to as residual biomass, and has much potential to be utilized in useful manner fulfilling the need for more sustainable waste management systems worldwide. Figure 1 shows the distribution of food waste source as per global average (kg per capita per year).

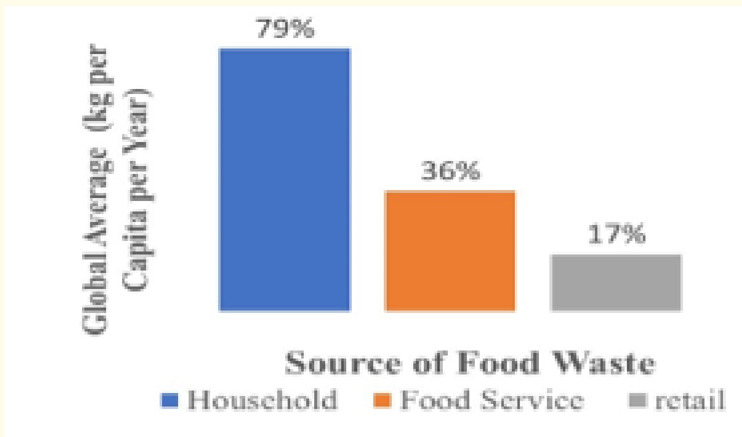


Figure 1: *United Nations Environment Programme (2024) [6]. Food Waste Index Report 2024, Nairobi.*

In order to reduce environmental concerns, several countries took positive initiatives to convert fruit and vegetable waste into valuable bio-products. Europe, the United States, and China have established biorefineries and zero-waste policies to recover high-value compounds and produce items like biofuels, biodegradable packaging, cosmetics, animal feed, and nutraceuticals [7,8]. Historically, the concept of waste repurposing began with composting and progressed through enzymatic conversion, microbial fermentation, and, more recently, green extraction and nano-encapsulation technologies [9]. These advances reflect a global shift toward circular economies, where waste is no longer viewed as a burden but as a resource that contributes to environmental resilience and economic innovation.

Despite Pakistan's status as a leading agricultural nation- producing staples like mangoes, citrus fruits, tomatoes, onions- it remains in the early stages of structured waste valorization. Recent studies estimate substantial post-harvest loses of approximately 30 - 40% for fruits and vegetables primarily due to inadequate handling, poor cold storage, and inefficient marketing infrastructure [10,11]. Most of the waste is either discarded or used informally as animal feed or compost, with minimal efforts directed toward high-value product development. Recent studies from Pakistan have shown promising results in using organic waste for bio methanation [12]. However, the country still lacks comprehensive strategy that includes effective policies, industrial innovation, and R&D investments. Compared to global progress, Pakistan lacks in both research and implementation, and urgent attention is needed to harness this underutilized biomass to meet the dual goals of environmental sustainability and economic growth.

Seasonal fruits and vegetables in Pakistan and their corresponding waste

Pakistan's agricultural diversity, driven by its unique agro-ecological zones, allows for the cultivation of a wide range of seasonal fruits and vegetables throughout the year. Fruits such as citrus (*Citrus spp.*), mango (*Mangifera indica*), guava (*Psidium guajava*), and date palm (*Phoenix dactylifera*) dominate the plains of Punjab and Sindh, particularly from Multan to Hyderabad. Banana (*Musa spp.*) thrives in the coastal areas of Sindh, while temperate fruits including apple (*Malus domestica*), peach (*Prunus persica*), pear (*Pyrus spp.*), and plum (*Prunus domestica*) are cultivated in the cooler regions of Khyber Pakhtunkhwa (KPK) and northern Punjab. Notably, Balochistan is recognized as the "Fruit Basket of Pakistan," producing over 60% of the nation's peach, apricot, and pomegranate, 34% of apples, 70% of dates, and 90% of grapes due to its arid climate that minimizes fungal infestations and enhances shelf life [13-15].

Vegetable production is similarly influenced by seasonal variations, falling into *Kharif* (summer) and *Rabi* (winter) categories. The main vegetables grown include potato (*Solanum tuberosum*), onion (*Allium cepa*), tomato (*Solanum lycopersicum*), chili (*Capsicum annuum*), turnip (*Brassica rapa*), okra (*Abelmoschus esculentus*), carrot (*Daucus carota*), and cauliflower (*Brassica oleracea var. botrytis*). Punjab leads with more than 60% of the country's vegetable production, especially in crops like potato and carrot, while Sindh and Balochistan contribute significantly to onion, tomato, and chili cultivation. Despite this year-round production capability, yield gaps remain due to low seed quality, outdated cultivation methods, and post-harvest losses [16-18]. In Pakistan, substantial quantities of fruits and vegetables are lost or wasted at various stages of the supply chain due to inadequate harvesting practices, inefficient post-harvest handling, transportation limitations, poor storage infrastructure, and weak market systems. According to the United Nations Environment Programme (UNEP, 2021), approximately 45% of globally produced fruits and vegetables are wasted, with similar or even higher rates reported in Pakistan's perishable produce sector. The Food and Agriculture Organization (FAO, 2023) also highlights that fruits and vegetables account for the highest share of global food losses, largely due to their perishability and post-harvest vulnerability.

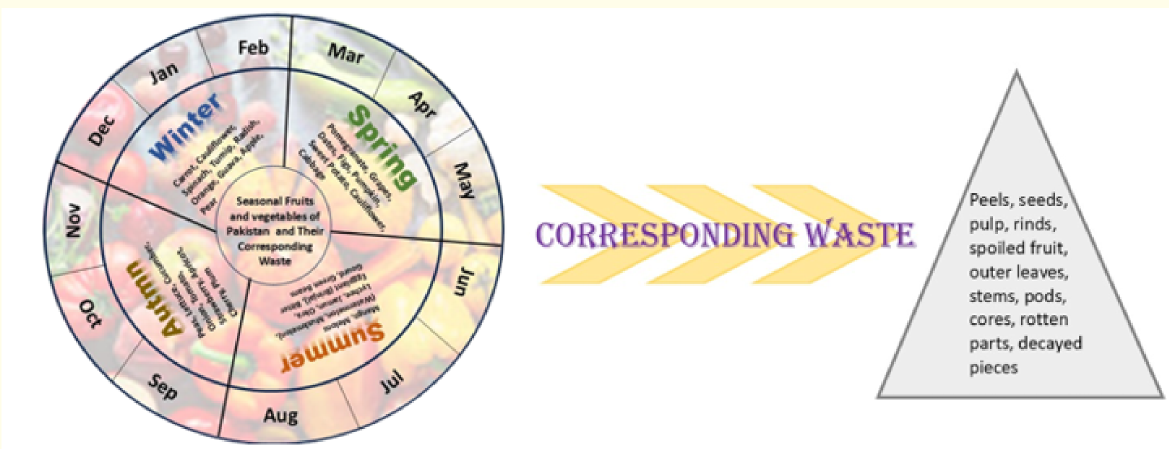


Figure 2: *Seasonal fruits and vegetables in Pakistan and their corresponding waste.*

Fruits and vegetables waste: Definition, types and its biochemical composition

Definition

Fruit and vegetable waste (FVW) comprises edible and inedible constituents obtained from fruits and vegetables that are discarded from human food supply chains at various phases, including harvest, post-harvest, handling, processing, retail, and consumption [19]. This waste stream is characterized by its heterogenous composition, high moisture content, and biodegradability. Global estimates indicate that FVW accounts for approximately 13 - 19% of total food production, as reported by the Food and Agriculture Organization (FAO) and United Nations Environment Programme (UNEP). The fundamental factors contributing to FVW are inherent perishability of produce, inadequate post-harvest management practices, and stringent cosmetic standards in retail markets. The quantification and characterization of FVW are necessary for developing effective waste management strategies and optimizing resource utilization in the agri-food sector. Table 1 contains types of wastes and biochemical composition along with utilization.

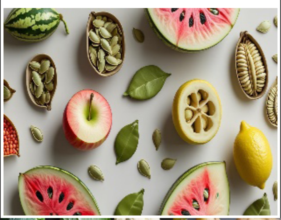
Type of Waste	Source (example)	Composition	Applications	Reference
 	Fruit peels (e.g. citrus, banana, pineapple, apple, grape) and vegetable peels (e.g. potato, carrot, onion) from processing	High in carbohydrates and fiber (cellulose, hemicellulose, pectin, and starch - e.g. ~50% DW starch in potato peels), plus proteins, lipids, and bioactive compounds (e.g. flavonoids in onion skin, essential oils in citrus peel). Rich in vitamins (C, B) and minerals	Animal feed, compost/fertilizer, bioethanol or biogas (anaerobic digestion). Extraction of high-value compounds: pectin (from citrus peels), dietary fiber and starch additives, antioxidants (carotenoids from carrot peel, quercetin from onion). Bio-based materials (edible films, activated carbon from peels)	[20-23]
	Fruit pomace (apple pomace, citrus pulp, grape pomace, etc.); vegetable pulp (tomato pomace, carrot pulp) from juicing or canning	Mainly fiber and sugars. Non-starch polysaccharides often make up 35-60% of dry weight, consisting of pectin (1.5-13%) cellulose (7-44%), hemicellulose (4-34%), and lignin (up to ~69%). Carrot pomace, for example, contains ~55% dietary fiber (mostly insoluble cellulose/lignin) and residual sugars. Moisture is high but varies. Also contains vitamins and phenolics from the original produce.	Animal feed and fertilizer/compost; anaerobic digestion to produce biogas or bioethanol (high sugar content); extraction of pectin, pigments or antioxidants (e.g. grape seed polyphenols). Can be used as a dietary fiber supplement in foods, or fermented to value-added products (citric acid, lactic acid, etc.) Also raw material for biochar or activated carbon.	[24,25]
	Fruit seeds/kernels (mango seed, avocado pit, apple seeds, citrus seeds, grape seeds, etc.)	Often rich in oil/lipids, protein, and fiber. For example, mango seed kernels contain ~8-13% oil (with high unsaturated fats) plus starch and protein. Grape seeds are high in polyphenols (proanthocyanidins). Generally, contain fats (up to 10 - 20%), some starch, protein (5 - 15%), and phenolics.	Cold-press or solvent extraction of seed oils (food or industrial oil); animal feed (press-cake) or organic fertilizer; biofuel feedstock (biodiesel). Seed residues can be used for activated carbon or as bio fillers. Many are sources of antioxidants: e.g. grape seed extract for nutraceuticals, mango kernel fat as cocoa-butter substitute.	[26]
	Vegetable trimmings (broccoli stalks, cauliflower leaves, cabbage outer leaves, carrot tops, potato vines, etc.)	Mostly lignocellulosic fiber: high in cellulose, hemicellulose and lignin (similar to pomace). Contains vitamins (chlorophyll, carotenoids) and minerals. Protein content is generally low. Moisture is high. Composition varies, but fiber can exceed 40-50% DW. E.g. broccoli stems ~15% protein, 35% fiber. Often ~5-10% protein, ~30-50% fiber, rest ash/water.	Often used whole as animal fodder or compost. Can be fermented to biogas (due to high fiber) or composted into soil amendments. In some cases, food applications use stalk fiber or leaf extracts (e.g. chlorophyll pigments). Leftover greens may be dried for use as dietary fiber.	[28]

Table 1: *Types and its biochemical composition.*

Valorization pathways of residual biomass

Composting and organic fertilizers: Aerobic and anaerobic composting of fruit and vegetable residues enables nutrient recycling and soil health enhancement. Chakravarty and Mandavgane (2021) [28] conducted a two-stage co-digestion (anaerobic digestion followed by aerobic digestion) of FVW mixed with slaughterhouse waste water, yielding biofertilizer with C:N ratio of 10-11 and biogas output of approximately 16 L/kg of fruit waste and 13.2 L/kg of vegetable waste. This co-digestion resulted in lignin depletion (64 - 70%), promoting cellulose decomposition and leading to potential biofertilizer.

Animal feed applications: Fruit and vegetable residual biomass can be utilized efficiently as sustainable alternative feed constituents, especially for ruminants. Incorporation of FVW as traditional feedstuffs exerted positive impacts on digestion and ruminal fermentation and also showed improvement in milk production without negatively influencing the animal health. Fermentation of fruit and vegetable waste with selected microbes enhance protein digestibility and promote production of value-added bioactive compounds, increasing suitability of utilization in feedstuffs [29,30].

In vivo, diets supplemented with 10% FVW improved dry matter digestibility approximately 5 - 7% and plasma antioxidant capacity approximately 26 - 32% while reducing methane emissions by 4 - 5% [31].

Bioenergy production

A recent study optimized FVW co-digestion with market wastewater, achieving 717 ml/day under ideal process parameters (40°C, pH = 7.2, 10-day HRT) and approximately 73% VS and 79% COD removal was reported. This process proved very effective and sustainable as supported by strong model accuracy i.e. $R^2 = 0.995$ [32]. Moreover, the potential of fermenting mixed fruit and vegetable wastes using a yeast consortium of *Candida krusei* and *Hanseniaspora guilliermondii* for bioethanol production was evaluated in a study. Among the tested substrates, banana peels showed the highest ethanol yield, reaching 7.38% (v/v) at 24 hours, indicating the effectiveness of indigenous yeast-based fermentation for bioethanol production from biodegradable wastes i.e. FVW [33]. Similarly, another study investigated the potential of biochar derived from liquid fruit and vegetable waste to enhance soil quality and reduce nitrous oxide emissions (N_2O). Results demonstrated that adding 2% LWFB significantly decreased total N_2O emissions, achieving a reduction exceeding 97% while enhancing soil nitrogen and carbon content. Microbial analysis revealed that LWFB promoted microbial diversity and reduced nitrifying bacteria abundance, thereby suppressing N_2O production by enhancing its conversion to nitrogen (N_2) gas [34].

Extraction of functional compounds

The emerging valorization methods include thermal extraction methods i.e. microwave-assisted, pressurized-liquid, and subcritical water extraction and non-thermal extraction processes i.e. ultrasound-assisted extraction, high pressure processing and pulse electric field extraction to efficiently recover functional compounds i.e. flavonoids, pectin, and enzymes from FVW and has potential to replace conventional extraction methods [35]. Effective applications of these technologies led to significant increase in the recovery of bioactive compounds from FVW, while simultaneously decreasing environmental pollution and resource wastage [36].

Edible product innovations

Based on extensive analysis of prior research, Ingale., *et al*. highlighted that microencapsulation of bioactive compounds extracted from residual biomass of fruits and vegetables significantly enhance their stability, controlled release and bio-availability allowing their incorporation into edible products and nutraceutical formulations [37]. In a recent study, tomatoes coated with a 5% Zucchini-derived pectin edible coating demonstrated significant preservation benefits: reduced weight loss, enhanced retention of sugars and ascorbic acid and delayed ripening, resulting in a shelf-life extension as shelf life of uncoated tomatoes was 9 days which increases to 11 days in case of pectin coated tomatoes. The coating also displayed antimicrobial activity against *S. aureus* and *A. niger*, alongside 34.32% antioxidant activity at 1 mg/ml concentration demonstrating a scalable valorization approach employing FVW pectin for edible innovation [38].

Industrial applications of fruit and vegetable biomass

Food and nutraceutical industries

Efficient valorization of food waste particularly fruit and vegetable residual biomass offer a promising pathway toward enhancing food system sustainability. This residual biomass has been shown to possess significant nutritional value, making them suitable candidates for incorporation as functional ingredients. Fruit and vegetable wastes, widely generated during market and processing operations are increasingly recognized as rich sources of bioactive compounds with significant potential for development into both nutraceuticals and functional foods [39]. As a practical example, mango peel powder (MPP) was incorporated into biscuits at levels of 5 - 15% resulting in enhanced nutritional composition, significantly increased antioxidant activity and retention of acceptable sensory qualities. *In vitro* digestion tests based on INFOGEST protocol further confirmed that phenolics and flavonoids from MPP remain bio accessible post-digestion demonstrating functional relevance of this fruit-peel-fortified food product [40]. Other similar examples include vegetable byproducts from cruciferous crops have been effectively incorporated into functional foods, enhancing both nutritional value and health-promoting properties i.e. powdered broccoli and cauliflower residues have been utilized to fortify baked goods such as flat bread, bread and pizzas by partially replacing wheat flour [41,42], while cabbage processing wastewater has been transformed into vinegar with improved ester content, taste, and quality [43] and enzymatically treated to produce soluble dietary fiber capable of binding bile acids and regulating glucose release. Similarly, radish byproducts, including anthocyanin rich brine from lactic acid fermentation, serve as source of natural food colorants and antioxidants [44,45] and radish waste powder offers a natural nitrite alternative for meat preservation without compromising safety or quality [46,47].

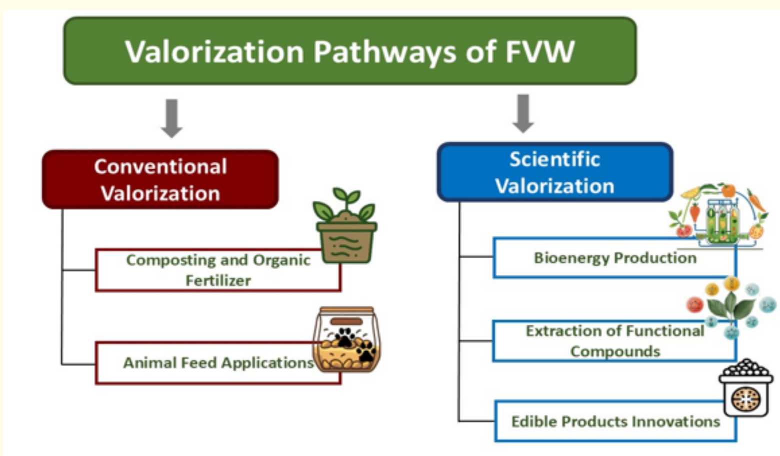


Figure 3: *Valorization pathways of residual biomass.*

Cosmetics and personal care

The growing demands for upcycled ingredients and green cosmetics are driving the cosmetic and nutraceutical industries. In one study, peels from exotic fruits i.e. *Litchi chinensis* and *Selenicereus undatus,* rich in antioxidants, vitamins, minerals and minerals, were subjected to propylene glycol-based extraction optimized through i-optimal and Box-Behnken experimental designs, with total phenolic content as the primary response variable. The optimized lychee peel propylene glycol extract (LPPG) demonstrated strong anti-tyrosinase activity (IC_{50} = 264.1 ± 16.9 μg/mL; inhibition = 92.33%) and potent antioxidant capacity, recording 2666.7 ± 68.71 μmol ascorbic acid/mL in the DPPH assay and 24774.68 ± 834.67 μmol ascorbic acid/mL in ABTS assay. The dried dragon fruit propylene glycol extract (DDPG) also exhibited notable antioxidant activity, with 1299.82 ± 20.80 μmol ascorbic acid/mL (DPPH assay) and 1510.51 ± 12.93 μmol ascorbic acid/mL (ABTS assay). These findings highlight the potential of optimized propylene glycol extraction of fruit residual biomass as a sustainable source of high value cosmetic ingredients [48]. Aligned with this approach, clementine peel and olive leaf extracts, obtained via Supercritical Fluid Extraction (SFE), exhibited notable antioxidant activity approximately 25% while maintaining keratinocyte cell viability above 90% and showing no cytotoxicity at concentrations up to 4% (v/v) within 24 hours [49].

Pharmaceutical potential

Bioactive constituents such as anti-oxidants, anti-microbials and anti-inflammatory agents obtained from fruit and vegetable waste hold considerable promise for incorporation into pharmaceutical formulations. Utilizing these compounds through optimized extraction, safety and efficacy validation, and regulatory compliance can foster sustainable pharmaceutical innovation while reducing environmental [50]. For instance, research on *Citrus aurantifolia* peel demonstrated that pectin obtained from this agro-waste (Yield: 34.4% w/w; esterification degree: 85.49%) can be effectively applied in designing Gastroretentive furosemide tablets. Optimization via central composite design indicated that a formulation containing 23.3% pectin and 5% effervescent agent achieved prolonged buoyancy (14.07s), strong mucosal adhesion (28.57g), high hydration capacity (254.08%) and controlled drug release (27.86% at 1h; 28.045% /). The study highlights citrus peel pectin as a sustainable, functional excipient with excellent retention and release characteristics for oral drug delivery [51]. Another study demonstrated that pectin isolated from orange peel waste (Yield: 25.26%, pH = 4.15) exhibited suitable physicochemical and flow properties with disintegration performance comparable to sodium starch glycolate. These findings suggest its potential as a sustainable substitute for synthetic super disintegrants in solid oral dosage form [52]. Similarly, another study optimized starch from *Mangifera indica* fruit through acid hydrolysis and microwave-assisted pre-gelatinization producing modified starch with significantly improved flow, compression, and swelling properties. The optimized product showed multi-functional potential as a binder, disintegrant, and diluent with performance comparable to conventional pharmaceutical excipients [53].

Biodegradable packaging and bioplastics

Recent advancements have focused on developing low impact bio-plastics from renewable animal and plant resources, particularly those rich in polysaccharides and proteins, as sustainable alternatives to conventional plastics for food packaging. Fruit and vegetable agrowaste have emerged as a valuable source of polymers such as cellulose, pectin, starch, and zein enabling production of eco-friendly materials with favorable mechanical barrier, and active protective properties. Incorporation of natural antimicrobials, antioxidants or pH sensitive compounds can yield smart and active packaging systems that extend food shelf-life. Scalable, low energy processes using green solvents allow these bioplastics and bio-composites to be formed into films or coatings, aligning with zero-waste and circular economy principles [54]. Following the progression in sustainable packaging technologies, white fraction of orange peel waste was utilized for nanocellulose production, while the pigmented fraction was processed to extract bioactive phytochemicals exhibiting antioxidant and antimicrobial properties. These extracts were incorporated with nano chitosan derived from shrimp shells to fabricate bioactive nanopackaging films, which effectively enhanced apple shelf life and preserved fruit quality [55].

Textile and dyeing industries

Agricultural and food processing wastes, rich in natural pigments, have demonstrated significant potential as sustainable sources of textile dyes, simultaneously addressing waste disposal challenges. Documented case studies report that dyes extracted from such wastes not only exhibit good color fastness, but in some cases, also function as natural mordants while imparting antibacterial and UV protected properties [56]. As a practical example, a recent study explored eco-friendly wool bleaching and dyeing using amino acids (lysine, betaine, and cysteine) and peptides, alongside natural pigments extracted from agro-waste such as red-cabbage, peppercorns, and onion peels. Onion peels showed strong coloring potential due to inherent natural modrants, while cysteine-based formulations achieved highest whiteness index. This approach not only reduced costs and energy consumption but also valorized agricultural waste, offering sustainable alternative to conventional textile processing methods [57].

Figure 4: *Waste to worth.*

Recent advances and case studies

Peel-derived antimicrobials

Case study: In Pakistan, food market generates large quantities of citrus and banana peels, which pose disposal challenges and potential health risks due to microbial spoilage. Researchers aimed to explore the potential of these peels as source of natural antimicrobial agents to reduce waste and improve safety. Ethanol and aqueous extractions were performed on banana, orange and lemon peels, followed by phytochemical analysis and antimicrobial testing against foodborne pathogens using disc diffusion and MIC assays (minimal inhibitory concentration). The extracts showed significant antimicrobial activity, with zones of inhibition up to 19 mm against *Salmonella typhi,* suggesting these peels wastes can be transformed into valuable natural preservatives because they exhibit bactericidal, fungicidal and diseasecontrolling agents for food products, thereby reducing environmental burden and enhancing food safety [58].

Methane-rich biogas production

Case study: Seasonal fruits and vegetables peels in Greece generate large quantities of high moisture organic residues that are unstable for single-stage conventional anaerobic digestion, hindering efficient biogas production. To address this challenge, a two-stage anaerobic digestion system was developed, utilizing a leach-bed reactor to facilitate hydrolysis and acidogenesis pf peel waste, followed by an up flow anaerobic sludge blanket (USAB) reactor for methanogenesis. This process effectively utilizes the peel residues by converting them into methane rich biogas, with methane yields increasing from approximately 265-278 to 360-375 L kg^{-1} VS, as microbial communities stabilized during continuous operation. This integrated approach validates a scalable and sustainable solution for managing seasonal peel waste, promoting renewable energy recovery and producing nutrient-rich digestate which is suitable for use as an organic fertilizer [59].

Replacement of chemical cleaners

Case study: Conventional household and industrial cleaners commonly contain toxic chemicals such as sodium lauryl sulfate (SLS), ammonia, phosphates, and chlorine-based compounds. These substances widely available in the market contribute to environmental pollution and pose long-term health risks including respiratory problems, skin irritation, endocrine disruption, and potential carcinogenic effects with prolonged exposure. Additionally, chemical residues contaminate water bodies, adversely affecting aquatic life and biodiversity. Addressing these challenges, Researchers have investigated the valorization of fruit and vegetable peel waste as rich in natural enzymes like pectinase, lipase, amylase, and cellulase. Their study involves using sustainable raw materials like peels of different vegetable and fruits (e.g. Potato, lemon, orange, banana, pineapple, and pomegranate) for producing eco-friendly enzymatic cleaners. The process involves aqueous extraction and fermentation of organic waste to enhance enzyme concentration. The resulting enzyme-based formulations demonstrated effective breakdown of organic stains and grease comparable to commercial detergents but without the harmful chemical footprint. This bioprocess not only reduces peel waste but offers a biodegradable, non-toxic alternative, mitigating health hazards associated with conventional cleaners while promoting circular economy principles [60-62].

Conclusion

Fruit and vegetable waste shows a significant, yet largely under-exploited, residual biomass with considerable potential for sustainable bioproduct development. Numerous global studies and industrial applications have demonstrated the feasibility of valorizing this waste into value-added products such as bioenergy, nutraceuticals, cosmetics, and biodegradable materials, thereby contributing to waste reduction and resource circularity. However, in Pakistan, progress in this domain is hindered by insufficient infrastructure, limited technological adoption, policy deficiencies, and fragmented waste management practices.

To realize the full potential of fruit and vegetable waste valorization, it is imperative to implement integrated strategies encompassing investments in advanced processing technologies, establishment of efficient collection and segregation systems, and the development of regulatory frameworks that incentivize waste conversion initiatives. Moreover, fostering synergistic collaborations between academic institutions, industry stakeholders, and government agencies will be critical to bridging the gap between research and commercialization, enhancing innovation capacity, and facilitating the scaling of pilot projects.

Adopting a circular bioeconomy approach focused on fruit and vegetable waste valorization can mitigate environmental pollution, reduce landfill dependency, and contribute to socio-economic development by generating employment and promoting sustainable livelihoods. Ultimately, the strategic utilization of this biomass aligns with global sustainability goals and presents a viable pathway for Pakistan to transform agricultural residues into economically valuable and environmentally benign products.

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