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Closing the Loop on Perishables: Transforming Horticultural Post Harvest Waste into Sustainable Future Foods

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Abstract
The Horticultural sector is a major challenge confronting the world by an estimated 18-55% of fruits and vegetable loss that occurs yearly leading to a nutritional loss of just less than USD 1 trillion as the economic burden. This article summarizes the paradigm shift of the traditional waste disposal model to a circular economy paradigm by upcycling post harvest side streams, including peels, seeds, and ugly produce, into high value future foods. We analysed green valorization technologies such as solar-assisted desiccation, refractance window drying, and ultrasound-assisted extraction that can recover bioactive compounds such as polyphenols and dietary fibers without leaving any toxic residues. Additionally, this article discusses the most important food safety issues, namely, concentration effect of pesticides and heavy metals caused by processing and suggests the development of horticultural safety levels. Combining techno economic analysis with consumer psychology, understanding this review identifies a prospect of bridging global nutrient shortages with the help of upcycled ingredients. Finally, the implementation of traceability 4.0 with blockchain and IoT to have a transparent supply chain and consumer confidence. This comprehensive solution will turn waste in horticulture into a sustainable resource that will be a part of a robust and circular global food system.

Keywords: Upcycling, Circular Economy, Post-Harvest Waste, Future Foods, Green Extraction, Food Safety, Traceability 4.0.

1. Introduction

The global horticultural production majorly encompasses fruits and vegetables, vital for global nutrition and economic growth. They significantly have various dietary components like carbohydrates, vitamins, minerals and phytochemicals (Yahia et al., 2019). Regardless of their importance, this sector faces significant challenges , particularly on post harvest losses and waste management (Shipman et al., 2021). Large quantities of fresh produce are wasted, which signifies both nutritional loss and waste of natural resources such as land , water and energy (Yahia et al., 2019). Estimation of post harvest losses of fruits and vegetables globally range between 28% and 55% annually (Karoney et al., 2024). While 33% of harvested produce is left unconsumed because of its high perishability (Shipman et al., 2021). Fruits and vegetables are the major contributors, accounting for 45% of total production that constitutes 38% of global food wastes (Blanckenberg et al., 2021).

In the future 2050, the global food systems need to be able to provide not only the necessary calories but also the necessary amount of protein and key micronutrients to support the increased population(Lozano et al., 2025). Other least exploited protein sources, such as plant based foods and food waste recycled proteins, are being proposed as solutions to protein demands in the future as an alternative to traditional animal food production (Avelar et al., 2022). Upcycled foods are protein rich, fiber rich and micronutrient rich and thus contribute to bridging the new nutrient deficiencies in the world as well as reducing consumption of resources and environmental footprint (Benvenutti et al., 2025).

Post harvest waste management involves integrated approaches using various strategies and technologies across the supply chain. The primary strategy is to minimize the waste generation by enhancing post harvest handling and storage practices (Sharma et al., 2024). Preservation techniques such as edible coatings, chemical treatments and radiation are widely used, technologies involving nanotechnology, active and intelligent packaging are now evolving (Rajapakshe et al., 2025).
Post harvest waste is specifically an opportunity for upcycling, while this waste includes fruit and vegetable waste, grain residues and other byproducts generated during various processes like harvesting, processing and storage (Sagar et al., 2024). Instead of disposing of these materials, which often leads to environmental burdens like methane emissions from landfills, upcycling transforms them into value-added products (Elgarahy et al., 2023). Various valuable components can be extracted from industrial food wastes. Plant derived wastes from vegetables, fruits and cereals are rich in phenolic compounds, pectin, carotenoids, and dietary fibers, which can be used as nutraceuticals, food additives, and biofertilizers (Sarangi et al., 2023).
Leafy green vegetables are characterized by exceptionally high tissue moisture content, a trait that underlies both their nutritional freshness and their acute postharvest fragility leafy vegetables are very highly perishable and must be utilized immediately after harvest, with their fast deterioration attributed to various biological and environmental factors, temperature playing a central role (Ambuko et al., 2017). Critically, once leafy vegetables lose more than 3% of their original fresh weight, they are rendered unsalable, a threshold reached within hours in the absence of adequate cold chain infrastructure (Ambuko et al., 2017). This narrow tolerance means that species such as Amaranthus tricolor, despite remaining nutritionally intact, are frequently discarded at the point of visible wilting rather than actual spoilage. Such prematurely rejected biomass, however, represents an underexploited feedstock for circular valorization; vegetable side streams, though frequently discarded or relegated to low-value applications, constitute a rich source of bioactive compounds and macromolecules with potential for high-value recovery (Pereira & Jiménez-Quero, 2025) .Reframing wilted leafy biomass in this light positions it not as terminal waste but as a time-sensitive resource for localized upcycling pathways.
Upcycled foods are a revolutionary approach of waste management as the food that would be disposed of is turned into valuable and nutritious products for human consumption (Spratt et al., 2020(Aschemann-Witzel, Asioli, Banović, Perito, Peschel, et al., 2023; Spratt et al., 2020). The Upcycled Food Association defines upcycled foods as utilizing ingredients that would otherwise not have been consumed, thereby preventing food waste (Aschemann-Witzel et al., 2022). This concept fundamentally agrees with the principles of circular economy, emphasizing the reduction of food loss and waste along the entire food supply chain (Rakesh & Mahendran, 2024).Globally, approximately about 30% of total production is wasted every year, which contributes to greenhouse gases (GHG) emission, loss of resources, and even to the extent of up to USD 1 trillion per annum (Isaac-Bamgboye et al., 2025). The environmental impacts are significant, and they involve eutrophication, pollution of soil and water and food supply chains (Isaac-Bamgboye et al., 2025). The main significance of upcycled foods about post harvest waste is they minimize environmental impact and maximize resource circularity.
Practically, upcycled foods are being marketed more as a defined consumer product like flours, snacks, baked goods, beverages and meat analogues (Grasso, 2020) (Benvenutti et al., 2025). Already available products are cereal bars and biscuits fortified with spent grain or oil seed cake , which is used by brewers, baked goods with coffee by product flours and snacks fortified with fruit peel or vegetable powders (Grasso & Asioli, 2020) These products enable consumers to engage in a circular food system directly by selecting products that provide their nutrition and eliminate food waste (Asioli & Grasso, 2021).
Upcycling as a part of the waste management hierarchy is a crucial integration for effective implementation. Traditional waste management tends to put more emphasis on reduction, then reuse, recycle, and recovery, with the least preferred option being disposal, where the food waste is converted to products that have a higher value, like bioplastics, bio-oil, biogas, and biofertilizers. This holistic solution not only to waste but also towards the development of new economic opportunities and products to advance the circular economy model (Di Fraia et al., 2023). A circular economy seeks to ensure that products and materials remain in use and regenerate natural systems and that waste is designed out (Conduit et al., 2023). This is in comparison to the traditional linear take-make-dispose model that results in a depletion of resources and environmental degradation. In the food sector a circular economy implies that one phase is used as input to the other in the same way that natural processes work (Conduit et al., 2023).
Food safety considerations are paramount when developing upcycled foods. Utilizing ingredients that might otherwise be discarded necessitates rigorous safe protocols to ensure that the final products are fit for human consumption(Aschemann-Witzel, Asioli, Banović, Perito, Peschel, et al., 2023).This involves comprehensive assessment of raw material quality, advanced processing methods, and stringent testing for potential contaminants or pathogens (Aschemann-Witzel, Asioli, Banović, Perito, Peschel, et al., 2023).
Sustainability, in the context of food systems, encompasses environmental, social, and economic pillars. Environmentally, reducing food losses and wastes directly mitigates climate change by curbing methane emissions from landfills, decreasing water and soil pollution, and preserving biodiversity. Economically, minimizing food losses and wastes reduces financial losses across the entire supply chain, benefiting producers, retailers, and consumers (Thorsen et al., 2023).
In addition to environmental benefits, the idea of upcycling after harvesting waste also leads to the social pillar of sustainability as it promotes food and nutrition security. Upcycled foods will enhance the availability and access to nutritious foods, particularly where undernutrition and micronutrient deficiencies exist amid sufficient production of nutritious foods worldwide (Guiné et al., 2021). Incorporating upcycled foods in sustainable food services and retail environments, stewardship aligns with social equity, thus contributing to the provision of lower waste and improved diets to diverse populations by the circular food system (Maynard et al., 2020).

Thereby, upcycling is a key strategy within this circular framework, transforming what was once considered waste into new, higher value products suitable for human consumption. This not only conserves resources but also minimizes waste generation and its associated environmental footprint.

2. New raw material

The transition from a linear "take-make-dispose" economy to a circular economy model necessitates the re-evaluation of what traditionally has been considered "waste" within the agricultural and food sectors. Postharvest side streams, which include peels, seeds, cores, and ugly produce, are increasingly recognized not as waste but as valuable secondary raw materials (Di Fraia et al., 2023). This paradigm shift is transforming discarded horticultural products into future foods and value added ingredients (Rakesh & Mahendran, 2024).

2.1 Characterization of By-products

Horticultural waste is a rich and diverse source of bioactive compounds and macronutrients that can be recovered and re-integrated into the food chain. These byproducts often contain higher concentrations of certain beneficial compounds than the primary edible parts of the fruits and vegetables (Elgarahy et al., 2023).

2.1.1 Dietary fibers

Fruits and vegetable peels, from citrus, apples, potatoes, and carrots, are particularly abundant in dietary fibers, including cellulose, hemicellulose, pectin, and lignin. These fibers are crucial for human digestive health, contributing to gut microbiota diversity, satiety, and the prevention of various chronic diseases. For example, apple pomace, a residue from juice production, is rich in dietary fiber and can be used to enrich other food products (Elgarahy et al., 2023).

2.1.2 Proteins

Seeds from various fruits and vegetables, often discarded, can be significant sources of plant based proteins. Grape seeds and watermelon seeds contain valuable proteins and amino acids that can be extracted and utilized as nutritional supplements in new food formulations. Protein rich fractions from these sources can contribute to addressing global demand sustainably (Elgarahy et al., 2023).

2.1.3 Polyphenols and other bioactive compounds

Peels, seeds, and even the pulp of many fruits and vegetables are excellent reservoirs of polyphenols, flavonoids, carotenoids, and other antioxidants. These compounds are known for their anti-inflammatory, anti-carcinogenic, and cardiovascular protective properties. For example, pomegranate peels are rich in ellagitannins, and citrus peels contain high levels of flavonoids like hesperidin and naringin, which possess strong antioxidant activities (Elgarahy et al., 2023). The extraction of these compounds through bio refinery solutions allows for their incorporation into functional foods, nutraceuticals, and even cosmetics (Sarangi et al., 2023).

Table 1: Nutritional and Functional Potential of Horticultural Side-Streams

No.	Side stream source	Bioactive compounds	Nutritional benefit	Reference
1	Citrus peels	Pectin,Hesperidin,Naringin	Gut health,antioxidants	(Elgarahy et al., 2023)
2	Apple pomace	Cellulose, Quercetin, Pectin	High dietary fiber, digestive aid	(Yahia et al., 2019)
3	Grape seeds	Proanthocyanin,Gallic acid	Cardiovascular protection, high value oils	(Sarangi et al., 2023)
4	Pomegranate peels	Ellagitannins,Punicalagin	Anti-inflammatory &antimicrobial	(Elgarahy et al., 2023)
5	Tomato peels	Lycopene, Carotenoids	Prostate health, natural red pigment	(Thorsen et al., 2023)
6	Mango peels	Polyphenols, Vitamin C,E	Immune support, high fiber content	(Sagar et al., 2024)
7	Watermelon seeds	Plant based proteins, Zinc	Sustainable protein source	(Avelar et al., 2022)

8	Potato peels	Chlorogenic acid, Phenolics	High antioxidant &fiber	(Sagar et al., 2024)
9	Banana peels	Resistant starch, Dopamine	Prebiotic properties, mood regulation potential	(Paramitasari et al., 2024)
10	Pineapple core/peel	Bromelain, Fiber	Proteolytic activity, anti-inflammatory aid	(Elgarahy et al., 2023)

Cell wall integrity (cellulose/pectin) declines with advancing harvest maturity due to hydrolase-driven pectin solubilization as the plant cell wall matrix, composed of cellulose microfibrils crosslinked to hemicelluloses and embedded with pectin, undergoes progressive disassembly during ripening, making over-mature produce structurally unsuitable for efficient upcycling. Pre-storage application of polyamines (putrescine, spermidine, spermine) counters this decline: polyamines are recognized anti-senescence regulators of plant senescence (Sobieszczuk-Nowicka et al., 2019) that bind to the cell wall, imparting structural strength, while reducing respiration and ethylene release and enhancing firmness, thereby preserving membrane integrity and retaining ascorbic acid and phenolic bioactives prior to storage.

2.2 The transition point:Fresh produce to secondary raw material

A significant portion of horticultural produce is rejected by retailers and consumers not because of safety or nutritional deficiencies, but due to superficial aesthetic imperfections (Rakesh & Mahendran, 2024). During market rejection, it functionally transits from fresh produce to a secondary raw material due to external criteria rather than intrinsic quality loss. During processing of fruits and vegetables (e.g., juicing, canning, freezing), significant amounts of peels, seeds, and pulp are generated. These byproducts are an unavoidable consequence of industrial food production and, from the moment they are separated from the main product, they assume to be in the status of secondary raw materials, ready for valorization. Generation of these secondary raw materials occurs when the original produce is unsuitable for intended use during harvesting, storage, and transportation due to physical damage, pest infestation, or improper handling but still contains valuable components (Sarangi et al., 2023).

The generation process is crucially influenced by regulatory and food safety standards. Materials must be handled and processed in a way ensuring the safety and compatibility for human consumption, even if they are sourced from waste. Robust quality control measures and proper preservation techniques are essential to maintain the integrity of these materials for upcycling (Melios et al., 2024).

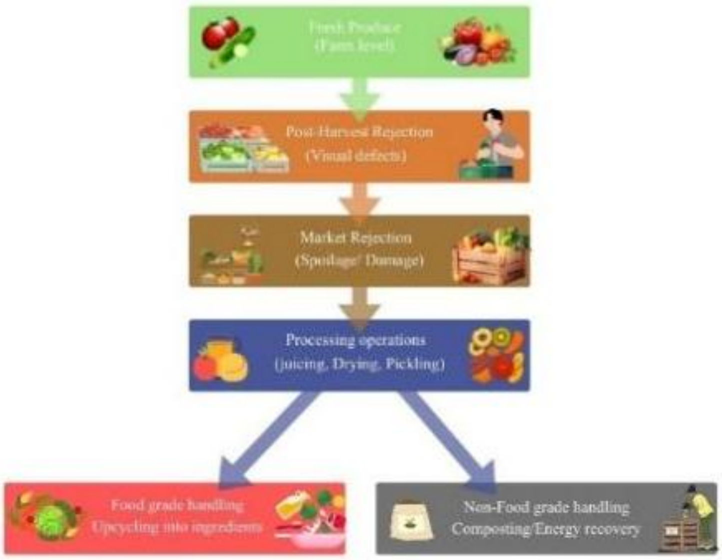

Figure.1Transition of fresh produce to secondary raw materials

3. Green valorization technologies

Green valorization technologies are the most important in terms of achieving a truly sustainable circular economy, especially the management of horticultural waste. These technologies are better because they have less impact on the environment, use less energy, and their ability to create safe and high quality upcycled products, without the use of toxic substances (Di Fraia et al., 2023). Green technologies allow converting post harvest waste into useful resources by preventing its rapid degradation and providing access to the extraction of useful compounds, thus ensuring the closure of nutrient loops and reducing the impact on the environment (Sagar et al., 2024). Scheduling of horticultural waste is essential in avoiding rapid deterioration that may result in loss of nutrients, as well as depletion due to microorganisms (Sarangi et al., 2023).

3.1 advanced stabilization

Conventional techniques usually use energy consuming procedures or chemical preservatives. Advanced stabilization techniques are crucial in preventing the rapid deterioration of produce by products by preserving their nutritional and functional value for food applications. This stabilization method inhibits the primary causes of nutrient loss and spoilage i.e., microbial development and enzymatic degradation.

3.1.1 Solar –assisted desiccation

A low carbon technique primarily used to reduce water activity (aw) in peels and pomace. Lowering the water activity (aw) prevents the growth of spoilage microorganisms, thereby extends the shelf life of the material and retains its nutritional content. This technique utilizes solar energy, a renewable resource, significantly reducing the energy requirement compared to conventional high temperature drying techniques that rely on fossil fuels. The mild drying process also retains the heat sensitive compounds and minimizes the degradation of valuable components present in the horticultural byproducts (Sagar et al., 2024). This approach aligns perfectly with circular economy principles by utilizing easily accessible natural energy to stabilize materials that would otherwise contribute to waste streams (Di Fraia et al., 2023).

3.1.2 Refractance window drying

A unique type of thin film drying is refractance window drying (RWD), which is a drying method that is superior in preserving heat sensitive vitamins and antioxidants compared to conventional drum drying. RWD is a process that employs infrared radiation and conduction by a hot water bath with thin plastic film to transmit energy to the product giving it a quick and soft drying process. RWD reduces heat-induced degradation of valuable biomolecules (e.g., vitamins, polyphenols, and pigments) that are easily destroyed by heat because of low operating temperatures and reducing drying time (Sagar et al., 2024). This loss prevention is essential in transformation of horticultural waste into nutritional and functional food products so that both the quality of the byproducts can be preserved and utilized in food products in future (Thorsen et al., 2023).

3.1.3 Freeze drying (lyophilisation)

This is a method for preserving heat sensitive compounds and maintains the structural integrity of byproducts. Freezing followed by sublimation of ice, preserving vitamins, antioxidants and other bioactive compounds. This method is highly energy intensive compared to solar drying, it can also enhance rehydration properties in food formulation (Sagar et al., 2024).

Unlike hard horticultural wastes such as citrus peels and woody stems, which contain lower moisture and can tolerate extended collection windows before processing fruit and vegetable waste inherently comprises inedible fractions such as peels, seeds, and pulp that vary in perishability across the supply chain (Sagar et al., 2018), soft leafy greens possess high initial moisture content and metabolic activity that accelerate spoilage. This is compounded by the fact that the time between waste generation and processing critically affects contamination, and waste can spoil during drying itself if drying time is too long or conditions are inadequate(Noori et al., 2022). Rapid stabilization methods such as solar desiccation are therefore essential, since a single sunny day under appropriate conditions can reduce moisture content of such waste to below 6%, effectively halting fermentation before further processing (Noori et al., 2022).

4. Upcycling waste into future foods

Upcycling is a significant strategy for addressing global food waste that also promotes sustainability, and enhancing the nutritional profiles (Kataria, 2025). This method aligns with the principles of circular economy by converting waste into high value products such as flour and extracts for several applications in the food industry (Javed et al., 2025). This method of valorization of waste by products with high nutritive value provides new opportunities in innovation (Boruah & Ray, 2025).

4.1 Upcycled foods

Flours made from fruit and vegetable byproducts are recently being recognized as functional ingredients (Benvenutti et al., 2025). Melon peel flour, which is rich in vitamins, polyphenols, and dietary fiber, has been incorporated into bakery products for enhancing nutritional and technological profile(Silva et al., 2023). Banana peel flour, which is an underutilized agro-industrial waste, a substitute for wheat flour in biscuits, improving the protein, starch, and soluble dietary fiber content (Paramitasari et al., 2024). This incorporation of such types of flours in bakery applications like bread, muffins and biscuits, improves the nutritional density, modifies dough rheology due to its fiber starch gluten interactions, and potentially reduces the glycemic response of end product (Bojnanska et al., 2024). Biscuits enriched with Acacia nilotica pod flour and raw banana flour show increased protein, fiber, and antioxidant content (Malik & Sindhu, 2025). Broccoli byproducts, including noncompliant florets are all processed into extracts and used in bakery formulations enriching them with healthy bioactive compounds (Fanesi et al., 2023).

Application of upcycled ingredients extends to snack food innovation. Extruded breakfast cereals can be benefited by adding fruit and vegetable byproducts, increasing the bioactive compounds (Santos et al., 2022). This offers a sustainable solution for food processing waste, apart from the nutritional improvement of snacks (Sagar et al., 2024). Consumers are increasingly looking for healthier options in their diet, while upcycled ingredients are a good means to meet this demand and also promotes environmental responsibility (Kataria, 2025).

Table 2: Summary of Upcycled Food Applications (Future Foods)

No.	Upcycled Ingredient	End Product Application	Impact	Reference
1	Melon Peel Flour	Bakery (cakes,Muffins)	Enhanced Vitamins and Polyphenols	(Silva et al., 2023)
2	Banana Peel Flour	Biscuits, Cookies	Increased resistant starch and mineral content	(Paramitasari et al., 2024)
3	Tomato Peel Powder	Fortified Wheat Flour	Significant boost in Lycopene and fiber	(Thorsen et al., 2023)
4	Acacia &Banana flour	Biscuits, Cookies	HIgh antioxidant and protein content	(Malik & Sindhu, 2025)
5	Broccoli Extract	Functional Bread	Enriched with cancer preventive glucosinolates	(Fanesi et al., 2023)
6	Mango Seed Kernel	Confectionary (Chocolates)	Alternative to cocoa butter, high antioxidant oil	(Sagar et al., 2024)
7	Apple Pomace	High Fiber Snack Bars	Improved texture and natural sweetness	(Elgarahy et al., 2023)
8	Grape Pomace	Fortified Pasta	Darker color, high tannin and fiber content	(Sarangi et al., 2023)
9	Coffee Silverskin	Energy Beverages	Source of caffeine and chlorogenic acid	(Sagar et al., 2024)

4.2 Consumer psychology and market acceptance of upcycled foods

Consumers also relate upcycled foods with both positive (innovation, recycling, reducing food waste) and negative (disgusting, sceptical, dislike) ideas (Aschemann-Witzel, Asioli, Banović, Perito, & Peschel, 2023). Food disgust sensitivity and food neophobia are always associated with a decrease in willingness to try or purchase upcycled foods as well as there are significant psychological obstacles for acceptance (Aschemann-Witzel et al., 2022; Di Cairano et al., 2025). In a survey among students, the willingness to consume ice cream or crisps declined when the participants received information about the product containing trimmings and peels, this indicates that the information of origin can develop the yuck reaction, despite the product itself being acceptable (Fox et al., 2025). Individual disgust sensitivity lowered the purchase intention of biscuits, beer and dairy products containing upcycled ingredients (Cela et al., 2023).

4.2.1 Sensory barriers

A recent review conducted with a sensory focus indicates when the formulation is adjusted correctly, addition of upcycled ingredients ≥10% alters the sensory properties such as darkening the colour, increasing bitterness and altering texture, yet still be well liked as the formulations are optimized (Melios et al., 2024). Empirical studies on biscuits, bars and other products discover that hedonic experience (taste, texture, aroma) is one of the major factors of acceptance, good sensory performance can overrule reuse concerns whereas as sensory quality can be rejected (Aschemann-Witzel & Stangherlin, 2021; Grasso & Asioli, 2020; Moshtaghian et al., 2021). Research on upcycled biscuits, pizza and other prototypes insists the taste and texture need to be built up with communication strategies like sensory testing and creating consumers by recommending to prevent gritty, bitter or visually repulsive products (Chiaraluce et al., 2024; Di Cairano et al., 2025; Grasso & Asioli, 2020). These results indicate a subtle approach, which is to integrate the frugality framing (not to waste food) with sustainability framing (benefits of climate and resources) and health /nutrition claims where appropriate. Meanwhile, the labels must not contain too graphic references to the waste or scraps that may cause greater disgust. Instead, they must focus on the safe and high quality byproducts, as well as, circular use of resources (Aschemann-Witzel & Stangherlin, 2021; Cao & Jang, 2025).

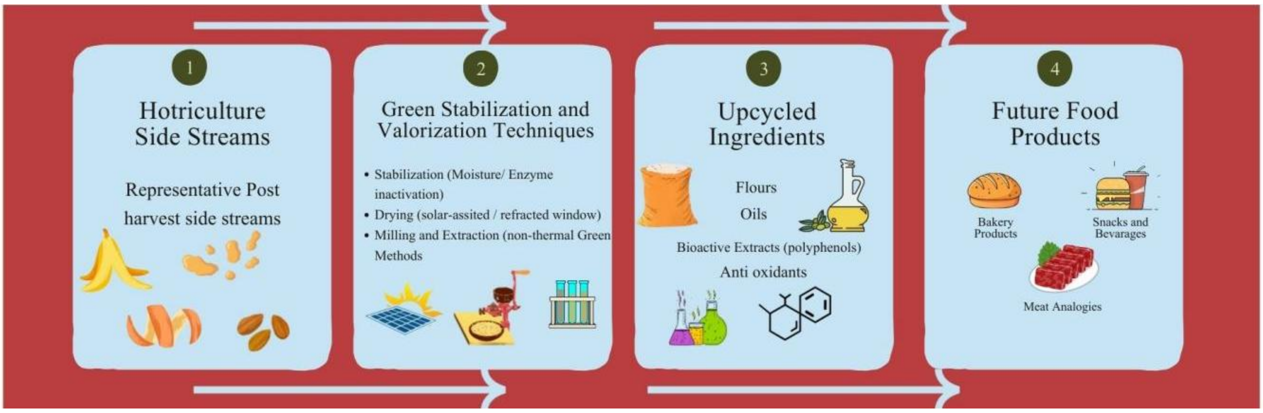

Figure 2. Upcycling pathways- Transforming side streams into Future Foods

5. Food safety and accumulation risks

Upcycling horticultural waste into new food products is a better way of utilizing waste but there arises the risks of chemical and microbial contamination in the final end product (Isaac-Bamgboye et al., 2025). The concentration factor is a critical issue in case of upcycled foods to counter the natural risks of unwanted compounds both chemically and microbiologically in high moisture and processed by products (Devi & M.J, 2025).

Table 3: Potential Contaminants and Accumulation Risks

No.	Contaminant	Sources	Risk in Upcycling	Reference
1	Pesticide Residues	Peels of citrus,apples and grapes	Drying processes remove moisture, concentrating non volatile residues by 5-10 times	(Thorsen et al., 2023)
2	Heavy Metals (Pb, Cd)	Root vegetables (Potatoes, carrots) and leafy greens	Metals from soil accumulate in peels and do not degrade during thermal processing	(Sagar et al., 2024)
3	Mycotoxins (patulin)	Bruised apples and pears	Fungal growth during logistical window between waste collection and processing	(Yahia et al., 2019)

4	Nitrates	Stems and leaves of leafy vegetables	Excessive nitrogen fertilizer use, high concentrations can lead to methemoglobinemia if upcycled	(Sagar et al., 2024)
5	Microbial Pathogens	High moisture pomace	Rapid fermentation and bacterial growth (Salmonella, E. coli) due to high sugar and water content	(Thorsen et al., 2023)
6	Antinutrients (Oxalates)	Spinach and beet stems	High concentration can interfere with mineral absorption (calcium,iron) in the final food	(Sagar et al., 2024)
7	Acrylamide	Potato peels	High surface area and starch content in peels increase acrylamide formation during high heat upcycling	(Sagar et al., 2024)
8	Cyanogenic Glycosides	Stone fruit kernels (Apricot, peach)	Release of hydrogen cyanide if kernels are ground into flour without proper detoxification	(Thorsen et al., 2023)

5.1 The concentration effect of processing

As horticultural side streams like apple pomace or citrus peel are dried to prepare powder that is stable with low moisture, higher the moisture loss higher the weight loss (80-90%), this causes increase in concentration of non- volatile compounds. This has an enigmatic impact on the safety of the final upcycled ingredients (Benvenutti et al., 2025).

5.1.1 Pesticide residues

The lipophilic pesticides get accumulated in the epicuticular wax present in the fruit peels (Devi & M.J, 2025). While these peels are processed into upcycled flours the residue in the resulting products may exceed the Maximum Residue Limits (MRLs) even if the whole fruit was within the compliance (Devi & M.J, 2025) Dehydration eliminates the water thereby, concentrating the existing amount of pesticides in peels, which leads to higher amounts in the final product (Isaac-Bamgboye et al., 2025). This highlights the importance of screening raw materials and strong control during processing in order to provide the safety of upcycled ingredients (Isaac-Bamgboye et al., 2025) .

5.1.2 Heavy metals

Heavy metals present in the skins and seeds of the horticultural products may be cultivated in soils contaminated with heavy metals like lead (Pb), cadmium (Cd) and arsenic (As) (Devi & M.J, 2025). Even if it is advantageous in recovering the resources, this does not satisfy the concept of clean products in a circular economy, mainly with agricultural waste, in which the source is potentially polluted(Aschemann-Witzel, Asioli, Banović, Perito, Peschel, et al., 2023). These heavy metals may be highly dangerous to human health if taken at high concentration (Devi & M.J, 2025). Testing horticultural waste prior to upcycling is the best way to avoid accumulation of heavy metals in the final food products (Isaac-Bamgboye et al., 2025).

5.2 microbial integrity and mycotoxin development

Due to the nature of horticultural waste, it is highly vulnerable to quick microbial spoilage as it usually has higher water content. This is a great challenge in preserving the materials from microbial contamination for use in upcycling.

5.2.1 The logistical window

Traditional post-harvest management practices leave waste in ambient condition prior to disposal, microbial proliferation occurs extensively. In the case of upcycling, the logistical window needs to be properly closed or reduced to a considerably short distance (Sagar et al., 2024). Immediate processing, drying and handling are important to avoid the growth of spoilage pathogens and then the development of detrimental microbial metabolites (Isaac-Bamgboye et al., 2025). The interval between the harvest and processing of horticultural byproducts is of significant concern in upcycling these substances (Isaac-Bamgboye et al., 2025).

5.2.2 mycotoxins

Fungal pathogens such as Aspergillus or (Nutrizio et al., 2024) Penicillium can grow quickly on wet pomace, resulting in the formation of heat resistant mycotoxins (e.g., patulin in apple waste) (Sagar et al., 2024). These toxins do not usually get eliminated through thermal processing techniques that are usually prevalent in the food manufacturing industry, and this can remain in the ingredient and present a substantial food safety risk(Sagar et al., 2024). Strict management of moisture levels, the use of fast drying methods and application of proper antimicrobial treatment during storage and processing are some of the mitigation approaches that are highly recommended (Isaac-Bamgboye et al., 2025). Mycotoxin contamination of raw materials and intermediate upcycled products needs to be closely monitored on a regular basis,which is highly essential (Sagar et al., 2024).

5.3 Proposing a horticultural safety threshold

Effective management of the risks associated with upcycling of horticultural waste is necessary. Setting up a threshold would serve as a critical determinant for deciding the wastes suitable for food upcycling versus alternative uses like composting or energy recovery (Devi & M.J, 2025). It is necessary to establish maximum permissible levels of pesticide residues, heavy metals (Pb, Cd, As), and other chemical hazards in the raw horticultural byproducts, taking the anticipated levels of the same processed products into account (Devi & M.J, 2025). Similarly, establishing limits of total viable counts, particular spoilage microorganisms, and absence of mycotoxins or its precursors at the place of collection and before processing (Sagar et al., 2024). Adopting effective traceability mechanisms for finding out the conditions under which their crops grow, the history of all the pesticides used in farms as well as the postharvest management of the harvested horticultural produce from which the waste is obtained (Isaac-Bamgboye et al., 2025). The proposed upcycling process should be thereby either decreasing or remove the potential hazards instead of concentrating them.

6. Sustainability and circular economy metrics

The idea of valorization of postharvest waste of horticultural produces by upcycling into future foods is a complex landscape where the metrics of sustainability and circular economy are the most important to evaluate the net effects on the environment, and the concept of life cycle assessment (LCA) is an essential tool to quantify its impacts, combined with the food waste hierarchy (FWH) (Nutrizio et al., 2024).

6.1 life cycle assessment (LCA) of future foods

One of the key issues in upcycling the horticultural postharvest wastes is whether the energy expenses of processing outweigh the environmental benefits (Nutrizio et al., 2024). This must be addressed through the LCA studies as they offer a systematic assessment of the environmental effects of raw material extraction to end processes involved in covering energy consumption, greenhouse emissions, and resource depletion (Aldama et al., 2023). Many of the processes of turning waste into new products which are energy intensive, like drying, extraction and fermentation (Elgarahy et al., 2023). The recurrent expenditures of power can be compensated by preventing liabilities to traditional ingredient manufacturing and waste disposal (Siddique et al., 2024). The avoided burden method of LCA gives credit to a product system with respect to the environmental pollution avoided by replacing it with a more detrimental product.

The effect of using upcycling of food waste could also result in unintentional side effects. Illustrate higher monogastric livestock production in China with more upcycled food waste as animal food is estimated to grow by 23-36% and produce 2.5-4.0 % more total acidification emissions (Long et al., 2025). This is why systemic changes should be considered carefully when introducing upcycling strategies (Long et al., 2025).

6.2 food waste hierarchy integration and net sustainability

The food waste hierarchy offers the system of prioritization of waste management strategies, in which usually prevention stands top, followed by redistribution, animal feed, composting, and at last disposal (Teigiserova et al., 2019). Upcycling horticultural Post Harvest Waste into human food falls within this ranking as one of the valorization methods. Nevertheless, its net sustainability as compared to other alternatives such as animal feed or composting needs multi criteria evaluation (Thorsen et al., 2023).

Horticultural wastes, such as fruit and vegetable peels, un harvested leaves, and by products of the processing methods, is a large source (Rodino, 2023; Sadeghi et al., 2023), that can be used to change into useful products . As an illustration, LCA and the Life Cycle Costing LCC have been used to determine the sustainability of the environment and economy of an orange peel waste valorization to animal feed (Dilek et al., 2025).

6.3 circularity indicators and resource efficiency

Upcycled foods have the potential to be beneficial in nutrition because these foods can be used as a substitute for less nutritious traditional food products. For example, refined wheat flour is replaced with upcycled tomato peel flour which contains an increased amount of fiber and lycopene intake (Thorsen et al., 2023). An analysis on the effect of upcycled food on sustainability reveals that this contributes to the generation with environmental, social, and economic benefits (Thorsen et al., 2023). This is the extent to which the upcycled products can be incorporated into the circular economy through cascading use , juice extraction will result in the production snacks from pomace, and the residual fiber will be socialized into a compost (Ogwu & Kosoe, 2025; Pomoni et al., 2024). The circular economy ensures that resources are utilized as far as possible, after getting maximum out of it then they need to recover and recycle products and materials at the end (Tamasiga et al., 2022; Yang et al., 2022).

6.4 Techno-economic analysis

The European scale TEA of tomato, potato, orange and olive byproducts bio refineries indicates that not every waste can be profitable, the notable economic viability of the product price, scale of plants and process set up is critical (Cristóbal et al., 2018). The production concentration is fewer but larger plants have the advantage of economies of scale, but are associated with the increased logistics costs of picking up dispersed waste (Cristóbal et al., 2018) The same type of work

on the food waste to biochemical and food waste bio refineries that use oils has positive returns on investment (ROI 12-15%; payback~7 years) when energy integration and co-product valorization are optimized (Patel et al., 2024).
Various comparisons are explicitly made between the amounts of energy spent and the cost of avoided burdens. Plants with bio refineries that can coproduce bioenergy or utilize food waste can be used to offset high electricity and steam requirements to enhance ROI and internal rate of returns (Elgarahy et al., 2023; Patel et al., 2024). Enzymatic dehydration of food waste through cost benefit analysis of the hydrolysis pathways reveal that conditions where bioactive peptides of high value are obtained in the food waste are still profitable in both optimistic and pessimistic scenarios, but low-margin products (bioethanol, organic acids) are highly sensitive to the cost energy and operating costs (Ghinea et al., 2025).
Simultaneously, the LCA-LCC research on high value foods of food waste points to the fact that biochemical pathways can use higher initial energy and require more steam, yet it can become economical and socio-economically competitive with the optimization of hotspots (thermal steps, solvent use, yields) (Albizzati et al., 2021). Pilot data to surplus food upcycling into retail foods indicates a modest and positive net revenue per product and significant savings in waste disposal, but environmental performance depends on formulation and energy consumption (Lehn & Schmidt, 2022).

6.5 Bioavailability and Nutritional Comparison of Upcycled Ingredients

Recycled products like tomato peel flour, fruit peel flours, millet bran concentrates or olive leaf extracts are gradually taking the place of traditional flour, fiber or nutraceutical. In case of fruit by product flours and millet by products all indicate a partial substitution of refined flour results in a substantial supplement of dietary fiber, polyphenols, or occasionally protein, and may confer antioxidant, prebiotic, anti diabetic and anti carcinogenic properties (Benvenutti et al., 2025; Kaur et al., 2025).
The green, non thermal extraction methods aim at preserving the structure and bioactivity of phenolics, carotenoids, and polysaccharides unlike thermal processes (Bekavac et al., 2025; Nutrizio et al., 2024). The food waste derived antioxidants can preserve or even increase in vitro antioxidant activity, when the extracted compounds can stay chemically accessible to human metabolism (Nutrizio et al., 2024). Equally, during valorization food derived polysaccharides and bioactives collected through either enzymatic or ultrasound assisted extraction have maintained functional properties applicable in cardiovascular and metabolic health (Nutrizio et al., 2024)..
Overall, the existing evidence conveys the fact that nutrients extracted by the green method of food waste are chemically bioavailable and maintain functional activity in vitro, and flour like upcycled foods enhance staple foods with fiber and bioactives (Nutrizio et al., 2024).

7. Management, policy and recommendations

The conversion of horticultural postharvest waste (PHW) into useful food products requires effective management, policy system and recommendations, especially in terms of traceability and regulatory environments.

7.1. Traceability 4.0: Certifying upcycled supply chains on safety and cleanliness

The inclusion of innovative digital technologies, including blockchain and the Internet of Things (IoT), is the solution that provides revolution in delivering the safety and the testing of supply chain in upcycling of horticultural wastes. As there are higher levels of risks of contaminant accumulation during upcycling especially in the concentrated form (eg., flours), transparent and immutable traceability systems are key to public health and consumer confidence (Dou et al., 2024).
The technology of blockchain with its decentralized and immutable ledger is able to trace all the stages of upcycling process, including the farm where the PHW is produced into end product (Ogwu & Kosoe, 2025). This encompasses the data of origin, processing parameters (e.g. temperature, drying time, mode of extraction, etc.), quality check and laboratory analysis of the presence of contaminants like pesticides and heavy metals (Dou et al., 2024; Sagar et al., 2024). All the information is time stamped and connected in a chain, it is incredibly difficult to modify it, this ensures authenticity and integrity of information (Ogwu & Kosoe, 2025). An example, a batch of upcycled fruit peel flour might have all the history of details available to regulators, manufacturers, and even consumers describing how it was extracted, the non thermal green extraction processes employed, and the safety clearance (Nutrizio et al., 2024).
IoT devices are utilized to supplement Blockchain with the automatic gathering of real-time data at each stage of the supply chain (Ogwu & Kosoe, 2025). Critical parameters like temperature and humidity that need to be controlled in the storage and transportation of postharvest waste can be monitored by sensors, avoiding its spoilage and keeping the material in its food grade quality (Sadeghi et al., 2023; Sagar et al., 2024). IoT sensors placed in smart packaging monitor the products during shipping and declare a condition that would be conducive in maintaining the quality and safety and directly enter this information into the Blockchain ledger (Ogwu & Kosoe, 2025). The implementation of traceability in horticultural postharvest waste is highly relevant as perishability and vulnerability to contamination is more, making strict monitoring of these are necessary in order to ensure its suitability for human consumption (Gautam et al., 2025).
Extending IoT and blockchain tracking to the farm harvest level allows quality assurance to begin at the source, since blockchain and IoT technologies applied to agricultural food supply chains have shown efficacy in addressing food fraud, contamination and systemic inefficiencies(Tang et al., 2024). Timestamped smart contracts could log harvest maturity and pre-storage anti-senescence treatments (e.g., polyamine application), as such contracts already record environmental and growth data with timestamped, verifiable evidence of when it was generated(Guo et al., 2025). This would certify baseline quality and safety before leafy green side streams enter upcycled processing, addressing the "garbage in–garbage out" risk of traceability systems left unverified at the source.

7.2 Policy recommendations and implementations

7.2.1 Redefining the concept of End of Waste

The existing laws usually define any substance existing a food processing plant as waste, even if it is a clean and a valuable side stream (Teigiserova et al., 2019). This categorization has strict transport, storage and processing regulations that may impede upcycling activities.

As a recommendation government need to adopt a Dual-Track system of classification, when the source of a side stream (e.g., clean fruit peels, vegetable stalks) is captured under the food grade environment and is to be used in food purposes, then it should not be in a waste status instead in by products status (Teigiserova et al., 2019). This would enable such materials to carry over the heavy regulatory conditions of transit and handling of waste in terms of value inherent in them and their intended application (Rakesh & Mahendran, 2024; Teigiserova et al., 2019). This strategy is according to the principles of the circular economy as it promotes the use of resources, at the very beginning (Pomoni et al., 2024).

7.2.2 Standardizing the upcycled label

Another major obstacle to the popularization of the circular food economy programs is the scepticism of the consumers towards the safety and quality products based on the earlier waste (Aschemann-Witzel & Stangherlin, 2021)

A high urgency of creating an international safety and sustainability certification of upcycled ingredients and products is needed (Rakesh & Mahendran, 2024; Thorsen et al., 2023). This certification must have strength, openness, and premise on stringent scientific examination. Mandatory Life Cycle Assessment (LCA) that is undoubtedly able to demonstrate that the upcycled ingredient has a reduced environmental impact than its conventional equivalent must be a major part of this certification (Aldama et al., 2023; Thorsen et al., 2023). This would offer the consumers credible confidence of safety as well as environmental improvements, which would result in a level of trust and a wider market demand towards upcycled foods (Aschemann-Witzel & Stangherlin, 2021).

7.2.3 Incentivizing clean collection infrastructure

The main problem of traditional waste management companies is that they are more oriented towards bulk disposal, volume instead of the maintenance of biological integrity and nutritional quality of materials (Elgarahy et al., 2023). This does not fit the needs of upcycling horticultural postharvest waste into food.

There needs to be specific tax incentives or subsidies to waste management companies and farm producers to invest in the cold chain waste logistics (Sadeghi et al., 2023; Sagar et al., 2024). This incorporates refrigerated storage, special collection trucks and fast transport networks that aim at maintaining the biological integrity of horticultural side streams on the source (Sagar et al., 2024). The foremost factor in any attempt to keep these materials in a condition that would allow their reuse by the people is to maintain them in such a state that they would not spoil or contaminate and become unusable (Sadeghi et al., 2023). These incentives would make the focus to be on preservation of the nutrients instead of waste disposal.

7.2.4 International regulatory alignment

A two track system of upcycled foods, one track of by products, which never become waste, and another track of materials that can regain the end of waste status, is appropriate but also reveals the contemporary international mismatch.

The waste framework directive (WFD) in the EU gives legal sets of clear categories of by products and the end of waste status. When a substance falls within the requirements of Article 6(1) EoW, that it is in common use, available on the market, passes technical and product standards, and not causing any overall negative environmental or health effects(Carla et al., 2021; Johansson, 2023). This framework ,when utilized appropriately, will enable the agri food scraps and residues to be treated as byproducts of EoW status and included in recycling targets and incorporated into circular models, as shown in the case of olive oil byproducts (Carla et al., 2021). Misclassification of the requirements leads to the entirety of waste disposal requirements and potential punishment and fine (Carla et al., 2021).

In the US, the food related federal instruments of the circular economy are more disjointed. No federal EoW definition has been equivalent to the EU WFD, but rather a patchwork of state based policies covering food waste prevention, donation, use of animal feed and landfill prohibitions (Ryen & Babbitt, 2022). National targets of reducing food waste by half are mostly voluntary and not enforced, and the heterogeneity of date labelling regulations and diversion requirements makes it difficult to scale the model of a circular business nationally (Ryen & Babbitt, 2022). Other waste streams also share similar contrasts like, in case of end of life solar PV, EU uses harmony based WEEE requirements, but the US does not have federal regulations on PV and has a wide range of differing state requirements (Nain & Anctil, 2024).

7.3 Risk based sampling protocols

As the accumulation risks are high, where the concentration of horticultural PHW during processing can inadvertently concentrate the amount of contaminants (Dou et al., 2024). The data driven and safety centric management of these materials should be provided. Adopt compulsory upcycled flours and other concentrated upcycled ingredients batch testing, and specifically address the top three regional pesticides and heavy metals found in horticultural crops (Dou et al., 2024). The protocol would entail analytical testing of every production batch to make sure that the concentration effect of each batch after processing does not result in the presence of contaminated levels which would affect the health of the population (Dou et al., 2024). This type of risk based sampling on the regional agricultural practices and familiarity with the profile of contaminants would form a very essential safety net and develop trust in the upcycled food products (Dou et al., 2024; Isaac-Bamgboye et al., 2025). Such policy suggestions and industrial implications will establish a favourable ecosystem that will hasten the movement of horticultural PHM towards a disposal challenge to a valuable resource capable of supplying future foods to a more sustainable and circular food system (Adedeji, 2022).

7.4 Commercial Implementation and Case Studies: Traceability 4.0 and IoT in practice

The traceability 4.0 of upcycled and waste to resource foods is an example that incorporates IoT sensory technology, cloud computing, AI analytics and blockchain to ensure safety, authenticity and compliance with the circular economy between the farm and the fork (Ellahi et al., 2023; Liu et al., 2023). Fruits and vegetables traceability review indicate that IoT, AI, blockchain and Big Data enablers of Industry 4.0 can enhance quality and safety, transparency, recall efficiency and waste reduction, but the high cost of implementation remains a barrier to full implementation by industries (Hassoun et al., 2023).

A digital based organic olive oil company that used a voluntary traceability system based on digital technologies to map operations, gather and process traceability information, and report credible product information to consumers, this increased chain transparency and sustainability performance (Latino et al., 2022). One of the healthcare supply chains under which smart containers of expired drugs, automated recall and recovery, and reductions in hazardous waste and energy use were made possible via IoT, cloud services and big data analytics, the identical CAB2IN framework is suggested to the circular, digitalized supply chain of other areas, such as food (Liu et al., 2023). Smart city pilot projects in which IoT sensors and AI analytics can be used to track food waste production, to optimize logistics of waste collection, and to enable circular waste management at the urban scale (Fatorachian et al., 2025).

Survey research on foodtech startups in Brazil and more generally indicates that digitization, traceability, SaaS services, and IoT are some of the most popular technologies to operationalize the business models based on a circle, including farm to table, reuse, and waste management niches (Hennemann Hilario da Silva & Sehnem, 2022, 2024). Real time tracking, surplus redistribution on digital platforms and traceability as a service are used in the startups for monetizing the streams of waste and ensuring regulatory compliance but high expenses and regulatory uncertainty are also a big hurdle (Hennemann Hilario da Silva & Sehnem, 2022).

8. Conclusion

A complete shift in the current linear model of take make dispose to a circular model of horticultural economies is a key boundary in the sustainability of the world, the reinventing of postharvest waste which was seen as a disposal liability into a source of nutrient rich future foods, a possible solution to the environmental crisis, as well as the nutrient gap that is plaguing the world's food supply as revealed in this article. By utilizing the green valorization technologies, the industry will be able to stabilize and recover high value bioactive compounds such as polyphenols and dietary fibers, and add them up to the human food chain instead of making them an element of landfill emissions.

However, the success of the upcycled food industry is dependent upon a safety first requirement on a large scale. Processing of food items on its own needs strict screening of pesticides and heavy metals with the help of innovative digital technologies, such as Traceability 4.0 and blockchain. In addition, the regulatory barriers should be minimized by changing the policy which redefines the clean side streams as by products and not waste. Overall, through technological innovation and proper alignment with consumer acceptance and solid safety measures, the food sector can turn the existing losses in the horticultural industry to a long term sustainable source of food supply to the ever increasing world population.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this review article.

References

1. Adedeji, A. (2022). Agri-Food Waste Reduction and Utilization: A Sustainability Perspective. Transactions of the ASAE. American Society of Agricultural Engineers. https://doi.org/10.13031/ja.14797
2. Albizzati, P., Tonini, D., & Astrup, T. F. (2021). High-value products from food waste: An environmental and socio-economic assessment. Science of The Total Environment, 755, 142466. https://doi.org/10.1016/j.scitotenv.2020.142466
3. Aldama, D., Grassauer, F., Zhu, Y., Ardestani-Jaafari, A., & Pelletier, N. (2023). Allocation methods in life cycle assessments (LCAs) of agri-food co-products and food waste valorization systems: Systematic review and recommendations. Journal of Cleaner Production, 421, 138488. https://doi.org/10.1016/j.jclepro.2023.138488
4. Ambuko, J., Wanjiru, F., Chemining'wa, G. N., Owino, W. O., & Mwachoni, E. (2017). Preservation of Postharvest Quality of Leafy Amaranth (Amaranthus spp.) Vegetables Using Evaporative Cooling. Journal of Food Quality, 2017(1), 5303156. https://doi.org/10.1155/2017/5303156
5. Aschemann-Witzel, J., Asioli, D., Banovic, M., Perito, M. A., & Peschel, A. (2022). Communicating upcycled foods: Frugality framing supports acceptance of sustainable product innovations. Food Quality and Preference, 100, 104596. https://doi.org/10.1016/j.foodqual.2022.104596

6. Aschemann-Witzel, J., Asioli, D., Banović, M., Perito, M. A., & Peschel, A. (2023). Consumer understanding of upcycled foods – Exploring consumer-created associations and concept explanations across five countries. Food Quality and Preference, 112, 105033. https://doi.org/10.1016/j.foodqual.2023.105033
7. Aschemann-Witzel, J., Asioli, D., Banović, M., Perito, M. A., Peschel, A., & Stefan, V. (2023). Defining upcycled food: The dual role of upcycling in reducing food loss and waste. Trends in Food Science & Technology, 132. https://doi.org/10.1016/j.tifs.2023.01.001
8. Aschemann-Witzel, J., & Stangherlin, I. (2021). Upcycled by-product use in agri-food systems from a consumer perspective: A review of what we know, and what is missing. Technological Forecasting and Social Change, 168, 120749. https://doi.org/10.1016/j.techfore.2021.120749
9. Asioli, D., & Grasso, S. (2021). Do Consumers Value Food Products Containing Upcycled Ingredients? The Effect of Nutritional and Environmental Information. Food Quality and Preference, 91. https://doi.org/10.1016/j.foodqual.2021.104194
10. Avelar, Z., Rodrigues, R. M., Pereira, R., & Vicente, A. (2022). Future food proteins—Trends and perspectives (pp. 267–285). https://doi.org/10.1016/B978-0-323-91001-9.00007-4
11. Bekavac, N., Krog, K., Stanić, A., Samec, D., Šalić, A., Benković, M., Jurina, T., Gajdoš Kljusurić, J., Valinger, D., & Jurinjak Tusek, A. (2025). Valorization of Food Waste: Extracting Bioactive Compounds for Sustainable Health and Environmental Solutions. Antioxidants, 14, 714. https://doi.org/10.3390/antiox14060714
12. Benvenutti, L., Moura, F., Zanghelini, G., Barrera, C., Seguí, L., & Zielinski, A. (2025). An Upcycling Approach from Fruit Processing By-Products: Flour for Use in Food Products. Foods, 14, 153. https://doi.org/10.3390/foods14020153
13. Blanckenberg, A., Opara, U., & Fawole, O. (2021). Postharvest Losses in Quantity and Quality of Table Grape (cv. Crimson Seedless) along the Supply Chain and Associated Economic, Environmental and Resource Impacts. Sustainability, 13, 4450. https://doi.org/10.3390/su13084450
14. Bojnanska, T., Kolesárová, A., Čech, M., Tancinová, D., & Urminská, D. (2024). Extracts with Nutritional Potential and Their Influence on the Rheological Properties of Dough and Quality Parameters of Bread. Foods, 13, 382. https://doi.org/10.3390/foods13030382
15. Boruah, B., & Ray, S. (2025). Emerging Techniques for Valorization of Fruit Processing Waste and Sustainable Utilization: A Review. Food and Humanity, 5, 100920. https://doi.org/10.1016/j.foohum.2025.100920
16. Cao, Y., & Jang, Y. (2025). Consumer perception of upcycled food labels. British Food Journal, 127. https://doi.org/10.1108/BFJ-02-2025-0216
17. Carla, Z., Chinnici, G., La Via, G., Bracco, S., Pecorino, B., & Mario, D. (2021). Regulatory Elements on the Circular Economy: Driving into the Agri-Food System. Sustainability, 13, 8350. https://doi.org/10.3390/su13158350
18. Cela, N., Giorgione, V., Fassio, F., & Torri, L. (2023). Impact of circular economy information on sensory acceptability, purchase intention and perceived value of upcycled foods by young consumers. Food Research International, 175, 113765. https://doi.org/10.1016/j.foodres.2023.113765
19. Chiaraluce, G., Bentivoglio, D., Conte, A., Lucas, M., & Finco, A. (2024). The second life of food by-products: Consumers' intention to purchase and willingness to pay for an upcycled pizza. Cleaner and Responsible Consumption, 14, 100198. https://doi.org/10.1016/j.clrc.2024.100198
20. Conduit, J., Karpen, I., & Willmott, T. (2023). User circularity practices: Adopting a user stewardship perspective for a circular economy. Academy of Marketing Science Review, 13. https://doi.org/10.1007/s13162-023-00262-6
21. Cristóbal, J., Caldeira, C., Corrado, S., & Sala, S. (2018). Techno-economic and profitability analysis of food waste biorefineries at European level. Bioresource Technology, 259, 244–252. https://doi.org/10.1016/j.biortech.2018.03.016
22. Devi, M., & M.J, G. (2025). Sustainable valorisation of postharvest waste for disease control and quality preservation in fruits and vegetables. Waste Management (New York, N.Y.), 210, 115253. https://doi.org/10.1016/j.wasman.2025.115253
23. Di Cairano, M., Condelli, N., Lomonaco, A., & Galgano, F. (2025). Agri-Food By-Products as Ingredients: Exploring Purchase Intentions Among a Sample of Italian Consumers. Foods, 14(15), 2664. https://doi.org/10.3390/foods14152664
24. Di Fraia, S., Sharmila V, G., Banu, R., & Massarotti, N. (2023). A comprehensive review on upscaling of food waste into value added products towards a circular economy: Holistic approaches and life cycle assessments. Trends in Food Science & Technology, 143, 104288. https://doi.org/10.1016/j.tifs.2023.104288
25. Dilek, F., Barampouti, E., Mai, S., Moustakas, K., Malamis, D., Martin, D., & Yetis, U. (2025). Orange Peel Waste Valorization: An Integrated Assessment of Environmental and Economic Sustainability in Animal Feed Production. Waste and Biomass Valorization, 16, 3873–3894. https://doi.org/10.1007/s12649-025-03044-2
26. Dou, Z., Dierenfeld, E., Wang, X., Chen, X., & Shurson, G. (2024). A critical analysis of challenges and opportunities for upcycling food waste to animal feed to reduce climate and resource burdens. Resources, Conservation and Recycling, 203. https://doi.org/10.1016/j.resconrec.2024.107418
27. Elgarahy, A., Eloffy, M. G., Alengebawy, A., El-Sherif, D., Gaballah, M. S., Al-wakeel, K., & El-Qelish, M. (2023). Sustainable management of food waste; pre-treatment strategies, techno-economic assessment, bibliometric analysis, and potential utilisations: A systematic review. Environmental Research, 225, 115558. https://doi.org/10.1016/j.envres.2023.115558
28. Ellahi, R., Wood, L., & Bekhit, A. (2023). Blockchain-Based Frameworks for Food Traceability: A Systematic Review. Foods, 12, 3026. https://doi.org/10.3390/foods12163026

29. Fanesi, B., Ismaiel, L., Nartea, A., Orhotohwo, O., Kuhalskaya, A., Pacetti, D., Lucci, P., & Falcone, P. (2023). Bioactives and Technological Quality of Functional Biscuits Containing Flour and Liquid Extracts from Broccoli By-Products. Antioxidants, 12, 2115. https://doi.org/10.3390/antiox12122115
30. Fatorachian, H., Kazemi, H., & Pawar, K. (2025). Digital Technologies in Food Supply Chain Waste Management: A Case Study on Sustainable Practices in Smart Cities. Sustainability, 17(5), 1996. https://doi.org/10.3390/su17051996
31. Fox, S., El Gourari, L., & Dermiki, M. (2025). Circular eating: A pilot study in France and Ireland exploring the factors affecting the willingness to consume upcycled food products containing peels and trimming from fruit and vegetables. Irish Journal of Agricultural and Food Ressearch, 64, 22–43. https://doi.org/10.15212/ijafr-2023-0118
32. Gautam, B., Negi, N., Bharti, B., Mohan, J., & Singh, D. (2025). Sustainable Management of Horticultural Waste. International Journal of Environment and Climate Change, 15(10), 1–9. https://doi.org/10.9734/ijecc/2025/v15i105040
33. Ghinea, C., Elena-Diana, U.-C., Ţâbuleac, R., Oprea, P., Coşbuc, E., & Gavrilescu, M. (2025). Cost-Benefit Analysis of Enzymatic Hydrolysis Alternatives for Food Waste Management. Foods, 14, 488. https://doi.org/10.3390/foods14030488
34. Grasso, S., & Asioli, D. (2020). Consumer preferences for upcycled ingredients: A case study with biscuits. Food Quality and Preference, 84, 103951. https://doi.org/10.1016/j.foodqual.2020.103951
35. Guiné, R., Pato, M., Amaro da Costa, C., Costa, D., Barracosa, P., & Martinho, V. (2021). Food Security and Sustainability: Discussing the Four Pillars to Encompass Other Dimensions. Foods, 10, 2732. https://doi.org/10.3390/foods10112732
36. Guo, T., Chen, Y., Ren, Q., Li, D., Bo, W., & Wang, X. (2025). Blockchain-Based Trusted Traceability Scheme for Food Quality and Safety. Journal of Food Quality, 2025(1), 5914078. https://doi.org/10.1155/jfq/5914078
37. Hassoun, A., Kamiloglu, S., Garcia-Garcia, G., Parra-López, C., Trollman, H., Jagtap, S., Aadil, R. M., & Esatbeyoglu, T. (2023). Implementation of relevant fourth industrial revolution innovations across the supply chain of fruits and vegetables: A short update on Traceability 4.0. Food Chemistry, 409, 135303. https://doi.org/10.1016/j.foodchem.2022.135303
38. Hennemann Hilario da Silva, T., & Sehnem, S. (2022). Industry 4.0 and the Circular Economy: Integration Opportunities Generated by Startups. Logistics, 6, 14. https://doi.org/10.3390/logistics6010014
39. Hennemann Hilario da Silva, T., & Sehnem, S. (2024). The utilization of Industry 4.0 technologies to enhance the circular economy through the engagement of stakeholders in Brazilian food technology companies. Business Strategy and the Environment, 34, 129–161. https://doi.org/10.1002/bse.3954
40. Isaac-Bamgboye, F., Onyeaka, H., Isaac-Bamgboye, I., Chukwugozie, D., & Afolayan, M. (2025). Upcycling technologies for food waste management: Safety, limitations, and current trends. Green Chemistry Letters and Reviews, 18. https://doi.org/10.1080/17518253.2025.2533894
41. Javed, A., Hashmi, M., Nadeem, U., Javaid, U., & Rehman, T. (2025). Valorization of vegetable waste for developing high-value food products: An upcycling approach. International Journal of Vegetable Science, 31, 1–57. https://doi.org/10.1080/19315260.2025.2515427
42. Johansson, O. (2023). The End-of-Waste for the Transition to Circular Economy: A Legal Review of the European Union Waste Framework Directive. Environmental Policy and Law, 53, 1–13. https://doi.org/10.3233/EPL-220064
43. Karoney, E., Molelekoa, T., Bill, M., Siyoum, N., & Korsten, L. (2024). Global research network analysis of fresh produce postharvest technology: Innovative trends for loss reduction. Postharvest Biology and Technology, 208, 112642. https://doi.org/10.1016/j.postharvbio.2023.112642
44. Kataria, P. (2025). Reviving Resources: The Role of Upcycled Foods in the Future of Food. Food Science and Nutrition Cases, 2025, fsncases20250019. https://doi.org/10.1079/fsncases.2025.0019
45. Kaur, R., Goyal, N., Panesar, G., & Panesar, P. (2025). Unraveling the nutritional potential of millet by-products through extraction of high value compounds for the development of novel food products. Food Chemistry, 472, 142983. https://doi.org/10.1016/j.foodchem.2025.142983
46. Latino, M. E., Menegoli, M., Lazoi, M., & Corallo, A. (2022). Voluntary traceability in food supply chain: A framework leading its implementation in Agriculture 4.0. Technological Forecasting and Social Change, 178, 121564. https://doi.org/10.1016/j.techfore.2022.121564
47. Lehn, F., & Schmidt, T. (2022). Sustainability Assessment of Food-Waste-Reduction Measures by Converting Surplus Food into Processed Food Products for Human Consumption. Sustainability, 15, 635. https://doi.org/10.3390/su15010635
48. Liu, L., Song, W., & Liu, Y. (2023). Leveraging digital capabilities toward a circular economy: Reinforcing sustainable supply chain management with Industry 4.0 technologies. Computers & Industrial Engineering, 178, 109113. https://doi.org/10.1016/j.cie.2023.109113
49. Long, W., Zhu, X., Weikard, H.-P., Oenema, O., & Hou, Y. (2025). Rebound effects may undermine the benefits of upcycling food waste and food processing by-products as animal feed in China. Nature Food, 6, 881–891. https://doi.org/10.1038/s43016-025-01219-7
50. Lozano, R., Smith, N., Fletcher, A., & McNabb, W. (2025). Strategies for Closing Global Nutrient Gaps: Enhancing Distribution and Supply. Proceedings of the Nutrition Society, 84. https://doi.org/10.1017/S0029665125100232
51. Malik, P., & Sindhu, S. C. (2025). Nutritional Enhancement and Sensory Evaluation of Biscuits Enriched with Acacia and Banana Flour. European Journal of Nutrition & Food Safety, 17(5), 371–383. https://doi.org/10.9734/ejnfs/2025/v17i51732

52. Maynard, D., Vidigal, M., Farage, P., Zandonadi, R., Nakano, E., & Botelho, R. (2020). Environmental, Social and Economic Sustainability Indicators Applied to Food Services: A Systematic Review. Sustainability, 12, 1804. https://doi.org/10.3390/su12051804
53. Melios, S., Johnson, H., & Grasso, S. (2024). Sensory quality and regulatory aspects of upcycled foods: Challenges and opportunities. Food Research International, 199, 115360. https://doi.org/10.1016/j.foodres.2024.115360
54. Moshtaghian, H., Bolton, K., & Rousta, K. (2021). Challenges for Upcycled Foods: Definition, Inclusion in the Food Waste Management Hierarchy and Public Acceptability. Foods, 10, 2874. https://doi.org/10.3390/foods10112874
55. Nain, P., & Anctil, A. (2024). End-of-life solar photovoltaic waste management: A comparison as per European Union and United States regulatory approaches. Resources, Conservation & Recycling Advances, 21, 200212. https://doi.org/10.1016/j.rcradv.2024.200212
56. Noori, A. W., Royen, M. J., Medveďová, A., & Haydary, J. (2022). Drying of Food Waste for Potential Use as Animal Feed. Sustainability, 14(10), 5849. https://doi.org/10.3390/su14105849
57. Nutrizio, M., Dukić, J., Sabljak, I., Samardžija, A., Fučkar, V., Djekic, I., & Režek Jambrak, A. (2024). Upcycling of Food By-Products and Waste: Nonthermal Green Extractions and Life Cycle Assessment Approach. Sustainability, 16, 9143. https://doi.org/10.3390/su16219143
58. Ogwu, M., & Kosoe, E. (2025). Innovative Approaches to Recycling, Upcycling, and Downcycling for Sustainable Waste Management. CleanMat, 2, 242–261. https://doi.org/10.1002/clem.70013
59. Paramitasari, D., Pramana, Y., Suparman, S., Putra, O., Musa, M., Pudjianto, K., Triwiyono, B., Supriyanti, A., Elisa, S., Singgih, B., & Ulinuhayani, M. (2024). Valorization of Lampung Province banana peel cultivars: Nutritional and functional characterizations for biscuit production and wheat flour substitution. Journal of Food Measurement and Characterization, 18, 9906–9920. https://doi.org/10.1007/s11694-024-02928-6
60. Patel, A., Sawant Desai, S., Mariam, I., Enman, J., Rova, U., Christakopoulos, P., & Matsakas, L. (2024). Innovative biorefinery approaches for upcycling of post-consumer food waste in a circular bioeconomy context. Chemical Engineering Journal, 494, 152990. https://doi.org/10.1016/j.cej.2024.152990
61. Pereira, P. F. M., & Jiménez-Quero, A. (2025). Circular valorization of green leafy side streams via pressurized liquid extraction techniques for recovery of bioactive compounds. Food Chemistry: X, 30, 102944. https://doi.org/10.1016/j.fochx.2025.102944
62. Pomoni, D., Koukou, M., Vrachopoulos, M., & Vasiliadis, L. (2024). Circular economy: A multilevel approach for natural resources and wastes under an agri-food perspective. Water-Energy Nexus, 7, 103–123. https://doi.org/10.1016/j.wen.2023.12.003
63. Rajapakshe, P., Rathnasinghe, N., Kaushani, K. G., Nilmini, R., Jayasinghe, R., Karunaratne, V., Wijesena, R., & Priyadarshana, G. (2025). Strategies to minimize post-harvest waste of fruits and vegetables: Current solutions and future perspectives. 6, 400–412.
64. Rakesh, B., & Mahendran, R. (2024). Upcycling of food waste and food loss – A sustainable approach in the food sector. Trends in Food Science & Technology, 143, 104274. https://doi.org/10.1016/j.tifs.2023.104274
65. Rodino, S. (2023). ASSESSING THE FEASIBILITY OF BIOECONOMY POTENTIAL IN THE HORTICULTURAL SECTOR: TRENDS, CHALLENGES AND OPPORTUNITIES. Fruit Growing Research, 39, 115–119. https://doi.org/10.33045/fgr.v39.2023.14
66. Ryen, E. G., & Babbitt, C. W. (2022). The role of U.S. policy in advancing circular economy solutions for wasted food. Journal of Cleaner Production, 369, 133200. https://doi.org/10.1016/j.jclepro.2022.133200
67. Sadeghi, K., Parnian-khajehdizaj, F., Ganjkhanlou, M., Faraji, R., & Abdollahi, Z. (2023). New Advances in Postharvest Technology: An Overview for Feed Production from Postharvest Wastes and By-Products. https://doi.org/10.5772/intechopen.111539
68. Sagar, N., Pathak, M., Sati, H., Agarwal, S., & Pareek, S. (2024). Advances in pretreatment methods for the upcycling of food waste: A sustainable approach. Trends in Food Science & Technology, 147. https://doi.org/10.1016/j.tifs.2024.104413
69. Sagar, N. A., Pareek, S., Sharma, S., Yahia, E. M., & Lobo, M. G. (2018). Fruit and Vegetable Waste: Bioactive Compounds, Their Extraction, and Possible Utilization. Comprehensive Reviews in Food Science and Food Safety, 17(3), 512–531. https://doi.org/10.1111/1541-4337.12330
70. Santos, D., Pintado, M., & Lopes da Silva, J. (2022). Potential nutritional and functional improvement of extruded breakfast cereals based on incorporation of fruit and vegetable by-products—A review. Trends in Food Science & Technology, 125. https://doi.org/10.1016/j.tifs.2022.05.010
71. Sarangi, P., Singh, A., Sonkar, S., Shadangi, K., Srivastava, R., Gupta, V., Parikh, J., Sahoo, U., & Muthusamy, G. (2023). Biorefinery solutions for food processing wastes: A sustainable bioeconomic perspective. Industrial Crops and Products, 205, 117488. https://doi.org/10.1016/j.indcrop.2023.117488
72. Sharma, C., Pathak, P., & Gautam, S. (2024). Potential of emerging “all-natural” edible coatings to prevent post-harvest losses of vegetables and fruits for sustainable agriculture. Progress in Organic Coatings, 193, 108537. https://doi.org/10.1016/j.porgcoat.2024.108537
73. Shipman, E., Yu, J., Zhou, J., Albornoz, K., & Beckles, D. (2021). Can gene editing reduce postharvest waste and loss of fruit, vegetables, and ornamentals? HORTICULTURE RESEARCH, 8. https://doi.org/10.1038/s41438-020-00428-4
74. Siddique, S., Grassauer, F., Arulnathan, V., Sadiq, R., & Pelletier, N. (2024). A review of life cycle impacts of different pathways for converting food waste into livestock feed. Sustainable Production and Consumption, 46. https://doi.org/10.1016/j.spc.2024.02.023

75. Silva, M., Gonçalves Albuquerque, T., Alves, R., Oliveira, M., & Costa, H. (2023). Melon peel flour: Utilization as a functional ingredient in bakery products. Food & Function, 15. https://doi.org/10.1039/D3FO05268K
76. Sobieszczuk-Nowicka, E., Paluch-Lubawa, E., Mattoo, A. K., Arasimowicz-Jelonek, M., Gregersen, P. L., & Pacak, A. (2019). Polyamines – A New Metabolic Switch: Crosstalk With Networks Involving Senescence, Crop Improvement, and Mammalian Cancer Therapy. Frontiers in Plant Science, 10. https://doi.org/10.3389/fpls.2019.00859
77. Spratt, O., Suri, R., & Deutsch, J. (2020). Defining Upcycled Food Products. Journal of Culinary Science & Technology, 19, 1–12. https://doi.org/10.1080/15428052.2020.1790074
78. Tamasiga, P., Miri, T., Onyeaka, H., & Hart, A. (2022). Food Waste and Circular Economy: Challenges and Opportunities. Sustainability, 14, 9896. https://doi.org/10.3390/su14169896
79. Tang, A., Tchao, E. T., Agbemenu, A. S., Keelson, E., Klogo, G. S., & Kponyo, J. J. (2024). Assessing blockchain and IoT technologies for agricultural food supply chains in Africa: A feasibility analysis. Heliyon, 10(15), e34584. https://doi.org/10.1016/j.heliyon.2024.e34584
80. Teigiserova, D., Hamelin, L., & Thomsen, M. (2019). Towards transparent valorization of food surplus, waste and loss: Clarifying definitions, food waste hierarchy, and role in the circular economy. Science of The Total Environment, 706, 136033. https://doi.org/10.1016/j.scitotenv.2019.136033
81. Thorsen, M., Mirosa, M., Skeaff, S., Goodman-Smith, F., & Bremer, P. (2023). Upcycled food: How does it support the three pillars of sustainability? Trends in Food Science & Technology, 143, 104269. https://doi.org/10.1016/j.tifs.2023.104269
82. Yahia, E., Fonseca, J., & Kitinoja, L. (2019). Postharvest Losses and Waste (pp. 43–69). https://doi.org/10.1016/B978-0-12-813276-0.00002-X
83. Yang, M., Chen, L., Wang, J., Msigwa, G., Osman, A., Fawzy, S., Rooney, D., & Yap, P. S. (2022). Circular economy strategies for combating climate change and other environmental issues. Environmental Chemistry Letters. https://doi.org/10.1007/s10311-022-01499-6