Circular horticulture: post-harvest management, value-addition and zero-waste strategies

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Abstract. Horticulture faces a dual challenge: post-harvest losses (PHL) accounting for up to 45% of global fresh produce output, and the systematic underutilisation of biomass residues generated throughout the value chain. This mini-review integrates current evidence across three interconnected pillars of sustainable horticultural systems. First, the metabolic and biochemical mechanisms underpinning post-harvest deterioration including respiration, ethylene-mediated ripening, cell-wall disassembly, and microbial proliferation are examined alongside the technologies designed to suppress them, encompassing cold-chain engineering, modified and controlled atmosphere storage, edible nanocomposite coatings, composite and active packaging, and non-thermal elicitation methods including cold plasma, 1-MCP treatment, and CRISPR-based cultivar improvement. Second, value-addition pathways are surveyed, covering green extraction platforms, nanoencapsulation of bioactives, functional food ingredient development, and conversion of horticultural residues into bio-based polymers and bioenergy through anaerobic digestion and pyrolysis. Third, zero-waste frameworks are assessed through the lens of the biorefinery paradigm, industrial symbiosis networks, and digital enablers including IoT sensors, hyperspectral imaging, and AI-driven supply-chain optimisation. Life-cycle and techno-economic evidence consistently demonstrates that integrating these three pillars delivers positive economic returns, reduced environmental burdens and improved resource efficiency relative to linear disposal models, across tomato, citrus, greenhouse and food manufacturing waste streams. Persistent barriers smallholder infrastructure deficits, regulatory fragmentation, and knowledge gaps in nanoencapsulate safety define the priority research agenda for fully circular horticultural systems.

Keywords: Biorefinery; Resource recovery; Edible coatings; Cold-chain engineering; Bioactive compounds; Circular economy; Zero-waste.

1 INTRODUCTION

Horticulture is arguably the most nutritionally dense yet physiologically fragile segment of global agriculture. Fruits, vegetables, edible flowers and medicinal herbs are characterised by high water activity (aw > 0.97), intense respiratory activity and a complex matrix of thermolabile secondary metabolites whose degradation rapidly undermines both quality and safety [1]. The FAO estimates that 45% of fresh fruits and vegetables produced annually are lost before consumption, equivalent to roughly 1.3 billion tonnes and USD 936 billion in economic value [2]. In sub-Saharan Africa and South Asia, where cold-chain infrastructure is sparse, PHL may exceed 50% for leafy vegetables and tropical fruits [3].

The consequences extend far beyond food insecurity. Each kilogram of wasted tomato embeds approximately 214 litres of virtual water, 0.64 MJ of embodied energy and 0.9 m² of cropland, together with associated agrochemical inputs and labour [4]. When this waste decomposes in landfills, it generates methane with a 100-year global warming potential (GWP) 28 times that of CO_2, making horticultural PHL a non-trivial contributor to anthropogenic greenhouse gas emissions [5]. At the same time, agro-horticultural processing generates enormous quantities of by-products - peels, seeds, pomace, stems, leaves and wash waters - that constitute concentrated repositories of polyphenols, carotenoids, dietary fibre, essential oils and structural polysaccharides [6]. The convergence of advanced extraction technologies, novel biorefinery architectures and growing consumer demand for natural bioactive compounds creates a historically unprecedented opportunity to transform these residues from disposal liabilities into high-value commodities [7].

This mini-review synthesises current evidence on (i) the mechanistic basis and technological landscape of post-harvest management; (ii) biochemically informed value-addition strategies for produce and processing residues; and (iii) systems-level zero-waste frameworks that cascade all biomass fractions into circular material and energy flows.

1.1 Review methodology

This mini-review was conducted by systematically searching the databases Scopus, Web of Science, PubMed and Google Scholar using the following keyword combinations: 'post-harvest losses', 'horticultural preservation', 'edible coatings', 'controlled atmosphere', 'non-thermal technologies', 'biorefinery', 'value-addition', 'zero-waste horticulture', 'circular economy', 'life-cycle assessment' and 'techno-economic analysis'. The search covered publications from 2003 to 2026, with priority given to peer-reviewed journal articles, systematic reviews, and authoritative institutional reports. Studies were included if they reported original or synthesised data on post-harvest quality preservation, biomass valorisation, or circular system performance in horticultural contexts. Book chapters and grey literature were excluded unless no peer-reviewed equivalent was available.

2 POST-HARVEST MANAGEMENT: MECHANISMS AND TECHNOLOGIES

2.1 Metabolic physiology of deterioration

Post-harvest deterioration is driven by the continuation of physiological and biochemical processes that remain active after harvest and progressively affect texture, flavour, colour, nutritional value, and marketability. Respiration constitutes one of the primary mechanisms of deterioration, as stored carbohydrates and organic acids are metabolised into carbon dioxide, water, and heat, accelerating senescence and energy depletion [8]. In climacteric commodities, ethylene plays a central regulatory role by stimulating respiration and activating ripening-related pathways, leading to softening, colour development, and tissue senescence [9].

Fruit and vegetable softening is closely associated with cell wall disassembly mediated by enzymes such as polygalacturonase, pectinases, cellulases, and other cell wall-modifying enzymes that degrade structural polysaccharides and reduce firmness [10]. Concurrently, metabolic changes involving the conversion of starch into soluble sugars and the degradation of organic acids contribute to the development of sweetness and flavour, while chlorophyll degradation and the accumulation of pigments such as carotenoids and anthocyanins determine characteristic colour changes during ripening [11]. Dynamic variations in antioxidants and bioactive compounds, including phenolics, flavonoids, and carotenoids, further influence nutritional quality and resistance to oxidative deterioration [12,13]. Microbial spoilage - through bacteria, fungi, and yeasts - causes decay, off-flavours, mycotoxin contamination, and substantial reductions in storage life and marketability [9]. Recent advances such as near-infrared spectroscopy (NIRS) enable non-destructive monitoring of physiological maturity, firmness, and internal quality attributes, supporting optimal harvest timing and reducing subsequent deterioration risks [14].

2.2 Temperature management and cold-chain engineering

Temperature management remains one of the most effective approaches for preserving post-harvest quality and extending storage life. Appropriate low-temperature storage reduces respiration rates, ethylene production, enzymatic activity, and microbial growth, thereby delaying ripening and senescence [11,15]. However, excessive exposure to low temperatures may induce chilling injury, manifested as tissue browning, internal breakdown, pitting, and off-flavour development, particularly in temperature-sensitive commodities [16]. Modern cold-chain engineering combines pre-cooling, refrigerated storage, and temperature-controlled transportation to maintain optimal environmental conditions throughout the supply chain. Technologies such as forced-air cooling, hydro-cooling, and vacuum cooling rapidly remove field heat after harvest [17,18]. Refrigerated transportation systems, including solar-powered mobile units, have further improved preservation in remote regions [19]. Energy-efficient systems incorporating phase-change materials and IoT-enabled smart sensors allow real-time monitoring of temperature, humidity, ethylene concentration, and gas composition, enabling rapid corrective actions and minimising post-harvest losses [14,20].

2.3 Modified and controlled atmosphere technologies

Modified atmosphere (MA), controlled atmosphere (CA), and modified atmosphere packaging (MAP) technologies regulate the gaseous environment surrounding horticultural products during storage and distribution. These systems typically reduce oxygen concentrations while increasing carbon dioxide levels, thereby suppressing respiration, delaying ripening, reducing ethylene action, and slowing senescence [21]. Atmosphere-based technologies help maintain firmness, texture, colour, flavour, and nutritional quality while limiting microbial deterioration [11,22]. Recent innovations include dynamic controlled atmosphere (DCA) systems that continuously adjust gas concentrations according to the real-time respiration rate and ethylene sensitivity of the stored produce [14,23]. Advanced MAP systems integrate high-barrier films, ethylene scavengers, and active packaging components to maintain favourable internal conditions and further extend shelf life [14]. Hypobaric storage represents another promising technology, operating under reduced atmospheric pressure to decrease respiration, ethylene production, and microbial growth for high-value export commodities [24].

2.4 Edible coatings, composite films and active/nano packaging

Edible coatings represent one of the most environmentally friendly post-harvest preservation technologies. Applied as thin semi-permeable layers, they reduce moisture loss, regulate gas exchange, delay ripening, and limit microbial contamination [9,11]. Natural biopolymers such as chitosan, alginate, and carrageenan are widely used due to their biodegradability, biocompatibility, and barrier properties [25]. The incorporation of bioactive compounds - essential oils, plant extracts, antioxidants, and natural antimicrobial agents - further enhances their protective efficacy [26,27].

Composite coatings combine two or more biopolymer classes - typically a polysaccharide with a protein or lipid component - to overcome the individual limitations of each matrix. Polysaccharide-protein composites (e.g., chitosan-whey protein, alginate-gelatin) provide superior mechanical integrity and water vapour barrier properties compared with single-component films, while lipid-polysaccharide bilayers (e.g., carnauba wax-hydroxypropyl methylcellulose) reduce water loss more effectively than either component alone [27,28].

Active packaging systems extend these principles beyond the product surface by incorporating functional agents directly into or onto packaging materials. Ethylene scavengers (potassium permanganate, zeolite-based materials), CO_2 emitters, oxygen absorbers, and antimicrobial sachets embedded in packaging films actively modify the headspace atmosphere to suppress physiological and microbiological deterioration throughout the supply chain [14]. Nano-bioactive systems further expand functionality: nanocomposite films incorporating zinc oxide nanoparticles, silver nanoparticles, or essential oil nanoemulsions exhibit improved mechanical strength, gas-barrier properties, and antimicrobial effectiveness while enabling the controlled release of active compounds at rates tuned by nanocarrier architecture. The integration of nanoparticles with natural bioactive substances provides enhanced protection against both microbial spoilage and physiological deterioration while preserving texture, flavour, aroma, and nutritional quality during prolonged storage [28].

2.5 Non-thermal elicitation technologies

Non-thermal technologies have gained increasing attention as effective alternatives to conventional chemical and thermal post-harvest treatments due to their ability to preserve nutritional and sensory quality while reducing environmental impacts. Ethylene management remains one of the most widely used approaches. Controlled ethylene application can synchronize ripening and improve product uniformity, whereas ethylene inhibitors such as 1-methylcyclopropene (1-MCP) delay ripening by blocking ethylene perception and maintaining firmness during storage [29,30]. Ethylene-releasing compounds such as ethephon are also used to promote uniform ripening and color development [31]. Cold plasma technology has emerged as an innovative non-thermal treatment capable of inactivating pathogens and reducing microbial contamination through the generation of reactive species without adversely affecting nutritional or sensory attributes [32,33]. Likewise, ozone treatments and ultrasonic cleaning provide effective, residue-free sanitation alternatives that enhance food safety while reducing microbial loads [14]. Biological control using antagonistic microorganisms represents a further sustainable strategy for suppressing post-harvest pathogens [34]. Genome-editing approaches such as CRISPR-Cas9 have been proposed as innovative tools for manipulating ripening-related genes and developing cultivars with improved storage potential and delayed senescence [35,36]. Collectively, these non-thermal technologies provide integrated solutions for enhancing post-harvest quality, reducing losses, and promoting sustainable horticultural production systems [9,30]. Fig 1 synthesises the five principal deterioration pathways reviewed across Sections 2.1–2.5 and their corresponding intervention technologies, illustrating the mechanistic relationships between biological drivers of quality loss and the preservation strategies designed to suppress them. Table 1 provides a comparative overview of the principal post-harvest preservation technologies discussed in this section, summarising their mechanisms of action, target commodities, and reported effects on quality preservation and loss reduction.

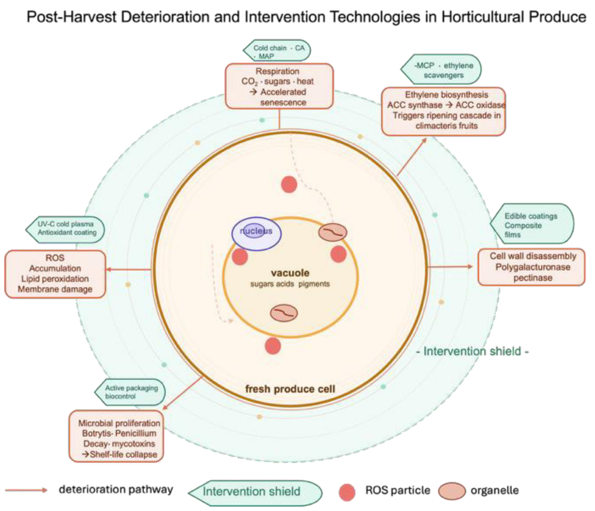

Fig. 1. Schematic representation of the five major post-harvest deterioration pathways and their corresponding intervention technologies, illustrated as a biological cross-section of a fresh produce cell. Deterioration mechanisms radiate outward from the cell interior: (i) respiration (CO_2 and heat accumulation → accelerated senescence), countered by cold chain, controlled atmosphere (CA) and modified atmosphere packaging (MAP); (ii) ethylene biosynthesis via the ACC synthase → ACC oxidase pathway triggering the ripening cascade in climacteric fruits, countered by 1-methylcyclopropene (1-MCP) and ethylene scavengers; (iii) cell-wall disassembly mediated by polygalacturonase and pectinase → tissue softening, countered by edible coatings and composite films; (iv) reactive oxygen species (ROS) accumulation → lipid peroxidation and membrane damage, countered by UV-C irradiation, cold plasma and antioxidant coatings; and (v) microbial proliferation (*Botrytis*, *Penicillium*) → decay, mycotoxins and shelf-life collapse, countered by active packaging and biological control. The outer teal ring represents the integrated intervention shield layer. ROS = reactive oxygen species; ACC = 1-aminocyclopropane-1-carboxylic acid; 1-MCP = 1-methylcyclopropene.

Table 1. Summary of principal post-harvest preservation technologies: mechanisms of action, target horticultural commodities, reported effects, and key references. ACP = atmospheric cold plasma; RNOS = reactive nitrogen and oxygen species; PAL = phenylalanine ammonia-lyase; SOD = superoxide dismutase; 1-MCP = 1-methylcyclopropene; CA = controlled atmosphere; MAP = modified atmosphere packaging; DCA = dynamic controlled atmosphere; RH = relative humidity; T = temperature; ML = machine learning.

Technology	Mechanism of action	Target commodities	Reported effect	Key references
Cold chain / precooling	Reduces Q10-driven respiration and ethylene production; slows enzymatic activity and microbial growth	Berries, leafy vegetables, tropical fruits	Significant slowing of physiological deterioration; critical for reducing PHL in developing regions; solar-powered units extend reach	[17–19]
Controlled atmosphere (CA)	Suppresses O2/CO2-mediated respiration and ethylene action	Apple, pear, kiwi, avocado	Maintains firmness, colour, flavour and nutritional quality; delays ripening and microbial deterioration during long-term storage	[21–23]
Modified atmosphere packaging (MAP)	Passive/active gas modulation within packaging; integrates ethylene scavengers and high-barrier films	Fresh-cut vegetables, berries	Extends shelf life and maintains quality during distribution; DCA systems allow real-time gas adjustment	[14,21]
Edible coatings (chitosan, alginate, composite)	Semi-permeable barrier reduces moisture loss, regulates gas exchange, limits microbial contamination	Strawberry, mango, tomato	Delays ripening and decay; composite and nano-bioactive coatings enhance antimicrobial efficacy and mechanical strength	[25–27]
1-MCP treatment	Blocks ethylene receptor binding; delays climacteric ripening and maintains firmness	Apple, pear, plum, avocado	Effective delay of ripening and quality loss in non-climacteric and climacteric fruit crops during storage	[30]
Cold plasma (ACP)	RNOS-mediated surface decontamination; inactivates pathogens without thermal damage	Leafy greens, strawberry, grain	5-log reduction in surface microbial load; preserves nutritional and sensory attributes; no chemical residues	[32,33]
UV-C irradiation	DNA disruption of surface pathogens; hormetic upregulation of PAL, SOD and antioxidant defence	Tomato, strawberry, grape	Reduces surface microbial contamination; elicits induced resistance and enhances secondary metabolite accumulation	[24]
IoT / smart sensors	Real-time monitoring of T, RH, ethylene, CO2 throughout supply chain	All supply-chain perishables	Enables rapid corrective actions; predictive quality assessment; ML integration improves demand-supply matching and loss prevention	[20,37]

3 VALUE-ADDITION: BIOCHEMISTRY AND BIOREFINERY PLATFORMS

3.1 Phytochemical inventory of horticultural by-products

Carotenoids (lycopene, β-carotene, lutein), polyphenols (anthocyanins, flavonols, hydroxycinnamic acids), terpenoids (limonene, carvone), glucosinolates and structurally diverse dietary fibres are concentrated in anatomical fractions seed coats, peels, pericarp, stems that are routinely discarded in processing streams [6]. Tomato pomace, for instance, yields lycopene at 140–250 mg kg^{-1} DW up to 10-fold higher than the fresh pulp alongside a pectin fraction with degree of esterification (DE) values of 68–74% [38]. Grape marc contains 5–10% total polyphenols by dry weight and constitutes the principal industrial source of proanthocyanidins and tartaric acid [39]. Olive mill waste water (OMWW) concentrates hydroxytyrosol (50–200 mg L^{-1}) and oleuropein aglycone, molecules with among the highest in vitro anti-inflammatory and cardioprotective activities recorded in plant secondary metabolites [40].

3.2 Green extraction platforms

The transition from conventional solvent extraction to green chemistry platforms is driven by the dual pressures of sustainability and bioactivity preservation. Supercritical CO_2 extraction ($scCO_2$; 31.1°C, 73.8 bar) achieves selective fractionation of lipophilic carotenoids and essential oils without thermal or solvent-induced degradation [41]. Ultrasound-assisted extraction (UAE; 20-40 kHz) accelerates solvent penetration through acoustic cavitation-driven cell-wall disruption, reducing extraction time by 60-80% and solvent consumption by 50% relative to conventional maceration [42]. Enzyme-assisted extraction (EAE) with cocktails of cellulase, hemicellulase and pectinase progressively depolymerises cell-wall polysaccharides, releasing bound phenolics and improving extractability of both target phytochemicals and functional polysaccharides in a single bioprocess [43]. These platforms are increasingly combined in sequential cascades - PEF pre-treatment followed by UAE then $scCO_2$ - to maximise total value recovery from a single residue stream [41,42].

3.3 Functional foods and nutraceutical applications

A critical value-addition pathway for horticultural by-products is their incorporation into functional foods and nutraceuticals. Horticultural processing residues serve as concentrated sources of dietary fibre, bioactive polyphenols, carotenoids and prebiotic oligosaccharides that can be incorporated into a wide range of food matrices [6]. Tomato pomace extracts enriched in lycopene are being incorporated into functional beverages, pasta and meat products as both natural colourants and health-promoting ingredients [38]. Grape marc polyphenol concentrates are used to fortify bakery products, yoghurts and dietary supplements, where they impart antioxidant and antimicrobial functionality [39]. Citrus peel pectin, with its gelation, emulsification and stabilising functionalities, serves as a versatile functional ingredient in beverages and confectionery [44]. The challenges of commercialisation instability during food processing, regulatory approval of novel ingredients, and consumer acceptance are being addressed through encapsulation and nanotechnology-based systems that improve bioactive stability and delivery [28].

3.4 Encapsulation and delivery engineering

The commercial translation of extracted bioactives demands solutions to chemical instability (oxidation, photodegradation), poor aqueous solubility and low oral bioavailability. Nanoencapsulation within lipid nanoparticles (solid lipid nanoparticles, SLN; nanostructured lipid carriers, NLC), biopolymeric nanospheres (zein, whey protein, alginate) and cyclodextrin inclusion complexes has demonstrated 3-10-fold improvements in lycopene and curcumin bioaccessibility in in vitro digestion models, while extending oxidative half-life by factors of 5-20 [28]. Electrospun polysaccharide nanofibers loaded with encapsulated plant extracts represent a frontier application, simultaneously providing active packaging functionality and controlled-release nutraceutical delivery within a single biodegradable matrix [45].

3.5 Bio-based materials and biopolymers

Pectin recovered from citrus, apple and beet residues (global production capacity ~50,000 t yr^{-1}) is an established commercial biopolymer with gelation, emulsification and prebiotic functionalities that position it as a direct sustainable substitute for synthetic hydrocolloids [44]. Nanocellulose - in the form of cellulose nanocrystals (CNC) and cellulose nanofibrils (CNF) isolated from lignocellulosic horticultural waste - exhibits tensile moduli of 100-160 GPa and enables the manufacture of packaging films with oxygen transmission rates competitive with multilayer petroleum-derived structures [46]. Lignin, the most abundant aromatic biopolymer on earth and an underutilised fraction of horticultural woody waste, is being valorised as a carbon precursor for activated carbons, as a UV stabiliser in bio-based coatings and as a feedstock for aromatic monomers via catalytic depolymerisation [47].

3.6 Bioenergy and cascaded resource recovery

Terminal fractions unsuitable for food or material valorisation are directed to bioenergy conversion. Anaerobic digestion (AD) of vegetable processing effluents and soft tissue residues (chemical oxygen demand 15,000-80,000 mg L^{-1}) yields biogas with methane content of 55-70% (vol/vol) and specific methane yields of 250-450 L CH_4 kg^{-1} VS, providing positive energy balances after parasitic energy subtraction [48]. For dry lignocellulosic residues (prunings, straw), pyrolysis at 400-600°C generates biochar with surface areas of 100-400 m^2 g^{-1} that improve soil water-holding capacity by 10-25% and sequester recalcitrant carbon for centuries, simultaneously enhancing soil microbial biomass and cation exchange capacity [49].

4 ZERO-WASTE HORTICULTURE: A CIRCULAR SYSTEMS ARCHITECTURE

4.1 The biorefinery paradigm applied to horticulture

The industrial biorefinery provides the conceptual and engineering template for zero-waste horticulture. In a fully integrated horticultural biorefinery, a single raw material stream is fractionated into: (i) premium-value bioactive extracts (nutraceuticals, pharmaceuticals); (ii) commodity functional ingredients (pectin, dietary fibre, protein isolates); (iii) bio-based materials (nanocellulose, lignin products); (iv) platform chemicals; and (v) bioenergy, in a cascade that maximises the economic return per unit dry matter while minimising waste generation (Mirabella et al., 2014). Life-cycle assessment (LCA) consistently identifies the cascade model as superior to single-valorisation routes in both environmental and economic performance (Almeida et al., 2024). Fig. 2 illustrates the circular zero-waste biorefinery cascade from harvest to soil amendment.

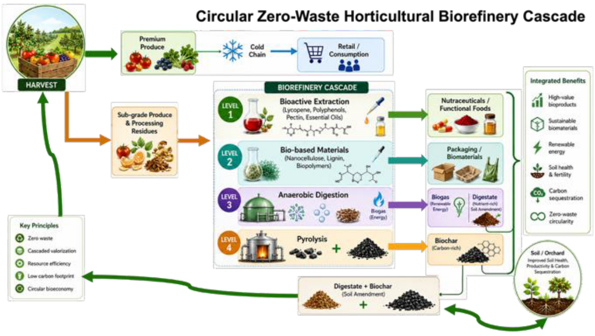

Fig. 2. Circular zero-waste horticultural biorefinery cascade illustrating the four-level valorisation hierarchy from harvest to soil amendment, integrating premium produce cold-chain distribution with cascaded processing of sub-grade produce and residues into bioactive extracts, bio-based materials, bioenergy, and soil amendments, forming a closed-loop circular bioeconomy.

4.2 Industrial symbiosis and spatial organisation

Zero-waste targets are most efficiently approached through industrial symbiosis models, wherein the by-product streams of co-located enterprises form a closed material network. The Agri-Food Industrial Symbiosis Networks (AFISN) concept has been piloted in several European agro-industrial clusters: for example, citrus-processing waste water feeds adjacent fermentation facilities producing probiotic beverages, whose spent biomass supplies AD plants, whose digestate fertilises the citrus orchards [7]. The Dutch Circular Horticulture model integrates greenhouse cultivation with combined heat and power (CHP) units fuelled by AD biogas, CO_2 enrichment of glasshouse atmospheres with CHP exhaust, closed-loop water recirculation and substrate reuse, achieving near-zero external resource demand and waste discharge [7,50].

4.3 Digital enablers of zero-waste systems

IoT-enabled sensor arrays (near-infrared spectroscopy, e-nose, hyperspectral imaging) deployed at packhouses and distribution centres now enable real-time, non-destructive prediction of ripeness, internal disorders and decay probability, allowing dynamic diversion of produce to the most appropriate channel before quality windows close [20,51]. Blockchain-based traceability systems provide immutable provenance records that underpin quality assurance claims and enable the premium pricing that makes circular business models economically viable [20]. AI and machine learning algorithms, trained on multi-year sensor datasets, are increasingly capable of predictive demand-supply matching that pre-empts oversupply events one of the leading causes of avoidable PHL at the retail stage [37].

4.4 Life-cycle and techno-economic performance

Quantitative appraisals of integrated zero-waste horticultural systems converge on consistent findings across multiple commodities and geographies, as summarised in Table 2. A biorefinery review of tomato processing waste encompassing lycopene, β-carotene and phenolic extraction combined with anaerobic digestion and composting demonstrates positive net present values and low payback times, confirming that cascade valorisation is economically viable relative to single-product or disposal routes [50]. For citrus waste, an integrated process producing ethanol, biogas, pectin and d-limonene in a single cascade yields 39.64 litres of ethanol, 45 m^3 biogas, 8.9 litres of limonene and 38.8 kg of pectin per tonne of fresh citrus waste, demonstrating that full-fraction utilisation with near-zero liquid discharge is technically achievable [52]. Valorisation of greenhouse horticulture waste through integrated biorefinery platforms has demonstrated feasibility across multiple biomass fractions and product streams, supporting the circular bioeconomy potential of horticultural residues [53]. Across a broader range of food manufacturing waste streams, circular biorefinery models consistently outperform linear disposal routes in both environmental and economic metrics, with GHG mitigation and energy efficiency gains documented relative to landfill and incineration baselines [7]. These findings collectively support the conclusion that integrated zero-waste horticultural systems deliver substantial environmental and economic improvements relative to linear models across a range of commodities and production contexts.

Table 2. Summary of valorisation strategies and reported outcomes for integrated zero-waste horticultural biorefinery systems. AD = anaerobic digestion; NPV = net present value; GHG = greenhouse gas.

Commodity / system	Valorisation strategy	Key reported findings	Environmental outcome	Reference
Tomato processing waste	Lycopene + β-carotene + phenolic extraction → AD + composting	Positive NPV and low payback times reported; biorefinery cascade outperforms single-valorisation routes	Reduced organic waste burden; closed carbon and nutrient loops	[50]
Citrus peel waste (orange)	Integrated process: pectin + d-limonene + ethanol + biogas production	39.64 L ethanol, 45 m^3 biogas, 8.9 L limonene and 38.8 kg pectin per tonne of citrus waste; pectin recovery 77.6%	Full utilisation of waste fractions; zero liquid discharge concept	[52]
Greenhouse horticulture waste	Sugar platform + biorefinery cascade (multi-product)	Valorisation feasible across multiple fractions (biomass, bioactive compounds, energy); circular bioeconomy potential demonstrated	Reduced landfill and incineration loads; improved resource efficiency	[53]

Food manufacturing waste (multiple commodities)	Cascade valorisation: food ingredient → biomaterial → bioenergy → soil amendment	Circular biorefinery models consistently outperform linear disposal in both environmental and economic metrics across multiple waste streams	GHG mitigation and energy efficiency gains vs. landfill; positive economic returns	[7]

5 CHALLENGES, GAPS AND FUTURE RESEARCH PRIORITIES

Notwithstanding the compelling evidence base, the transition from linear to circular zero-waste horticulture faces layered structural, regulatory and scientific challenges. Three critical bottlenecks merit particular attention.

Infrastructure and equity. The majority of horticultural PHL occur in smallholder farming systems in tropical and subtropical regions, precisely where cold-chain, packaging and processing infrastructure is most deficient. Innovations such as solar-powered mini-cold stores, low-cost evaporative cooling structures and village-scale biochar kilns are demonstrating proof-of-concept, but remain far from the scale needed to make a systemic difference [17,54].

Regulatory and market harmonisation. Novel food ingredient approvals for by-product-derived bioactives (polyphenol concentrates, nanocellulose, edible coating polymers) follow divergent regulatory pathways across the EU (Novel Food Regulation EC 2015/2283), the USA (FDA GRAS system) and Asian markets, creating substantial commercialisation barriers and discouraging investment in extraction infrastructure [55]. Standardisation of compositional characterisation, bioavailability testing and safety assessment methodologies is urgently needed to accelerate regulatory convergence.

Scientific frontiers. Key knowledge gaps include: (i) systems-level understanding of how post-harvest stress responses (ROS, ethylene, jasmonate signalling) interact with microbial community dynamics on produce surfaces [9].; (ii) the fate and bioavailability of nanoencapsulated bioactives through gastrointestinal digestion and their long-term safety profile [28]; (iii) multi-criteria optimisation frameworks that simultaneously maximise nutritional quality, food safety, value recovery and environmental performance across entire value chains [37]; and (iv) the sociological and behavioural dimensions of consumer acceptance of upcycled food products [56]

6 CONCLUSION

The evidence reviewed here demonstrates that post-harvest deterioration is a manageable metabolic process, controllable through cold-chain engineering, atmosphere modulation, bioactive and composite coatings, and non-thermal technologies. Simultaneously, horticultural processing residues represent underexploited phytochemical assets that can be cascaded into nutraceuticals, functional foods, biomaterials, and bioenergy within integrated biorefinery architectures. When coupled with digital intelligence and industrial symbiosis models, these approaches collectively deliver measurable reductions in environmental footprint and improvements in value-chain economics relative to linear systems. The most persistent barriers to adoption are structural rather than scientific: cold-chain inaccessibility for smallholder producers, regulatory fragmentation across jurisdictions, and insufficient decentralised processing infrastructure. Closing these gaps requires transdisciplinary research bridging plant physiology, food engineering, materials science, and digital technology, anchored by equity-centred design that prioritises the producers who bear the greatest burden of post-harvest losses. The scientific foundations for circular zero-waste horticulture are largely in place; translating them into accessible, scalable and inclusive systems remains the defining challenge and opportunity for the sector.

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