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Advances in value-addition of horticultural crops: postharvest shelf-life extension, clean-label preservation, minimally processed products, and byproduct valorization

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Abstract

India's horticulture sector is expanding rapidly, yet substantial value is lost through postharvest deterioration and quality downgrading within fresh supply chains. Recent NABCONS estimates for 2020–22 indicate postharvest losses of 6.02–15.05% in fruits, 4.87–11.61% in vegetables, and 1.29–7.33% in plantation crops and spices, with notable losses in tomato, mango, banana, onion, cassava/tapioca, chilli, turmeric, and black pepper. This review synthesises science-based pathways for value addition in Indian horticultural crops, focusing on major fruits and vegetables such as mango, banana, tomato, and onion, as well as high-value spices, while considering roots and tubers within the broader horticultural context. The review integrates the mechanistic basis of postharvest losses, including respiration, ripening, water loss, browning, pigment instability, microbial spoilage, and mechanical injury, with practical strategies for preservation and processing. It examines quality-retention approaches for minimally processed produce, including harvest maturity management, pre-cooling, cold-chain maintenance, modified atmosphere packaging, edible coatings, clean-label antimicrobials, and alternative sanitisation methods. Value addition is further highlighted through fresh-cut, ready-to-cook, ready-to-use, dehydrated, and fermented products, as well as by-product valorisation into functional ingredients and sustainable packaging materials. A matching framework is proposed to align crop perishability with feasible technologies across farm-gate, FPO/MSME, and industrial scales. Key research priorities include predictive shelf-life models, packaging–produce matching, validation of clean-label sanitation, energy-efficient cooling, and by-product valorisation supported by safety and techno-economic evidence.

Key words: Postharvest quality retention, Clean-label preservation, Minimally processed horticultural products, Smart and active packaging, Byproduct valorisation

India's horticulture sector has shifted from supplementary diversification to a leading contributor to agricultural value and nutrition. Recent national estimates put total horticultural production at about 367.72 million tonnes in 2024–25, which includes 114.51 million tonnes of fruits and 219.67 million tonnes of vegetables (PIB, 2025). At this scale, value-addition starts at harvest and extends through handling, cooling, storage, packaging, and transformation into products with longer shelf lives and higher market value.

A substantial portion of horticultural produce in India is lost or downgraded before reaching consumers or processors due to physiological deterioration, mechanical injury during harvest and transport, microbial spoilage, and inadequate temperature and humidity management. Efforts to reduce postharvest losses highlight that real improvement comes from integrated investments in technology, logistics, and operations rather than isolated interventions (PIB, 2025; Gulati *et al.,* 2024). For perishable crops such as mango, banana, tomato, onion, and certain spices—where attributes like aroma, colour, and cleanliness are critical—retaining postharvest quality is itself a means of value addition, preserving market grade, storability, and access.

While there is extensive literature on horticultural value-addition, it remains fragmented into themes like edible coatings, smart packaging, non-thermal -sanitisation, or byproduct valorisation. What is needed is an India-specific synthesis that links commodity physiology, supply-chain capacity, and practical technology bundles. Specific reviews cover coatings and packaging (Alemu *et al.,* 2025; Moradinezhad *et al.,* 2025; Du *et al.,* 2025), and national policies emphasise integrated cold-chain and value-addition infrastructure as essential for reducing waste (PIB, 2025). For practitioners in horticulture, the priority is to relate mechanisms of deterioration to preservation pathways and to address real bottlenecks in scale-up, standardisation, quality validation, safety assurance, and supply-chain integration.

Accordingly, this review synthesises science-based pathways for value-addition in Indian horticultural crops, with emphasis on major fruits and vegetables and high-value spices, while treating roots and tubers as one component of the broader horticultural matrix. It focuses

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on the mechanistic basis of postharvest loss, shelf-life extension, and clean-label preservation technologies; minimally processed and convenience products; valorisation of by-products into functional ingredients and packaging materials; and smart and sustainable packaging as an emerging frontier. The central aim is to identify actionable research gaps for Indian conditions rather than to repeat commodity-wise inventories of conventional processed products. As shown in Figure 1, value addition in horticultural crops should be viewed as a continuum that begins with postharvest loss prevention and extends through shelf-life extension, processing, packaging, and by-product valorisation.

Scientific basis of postharvest deterioration: mechanistic foundation of value -addition

Postharvest deterioration results from interacting physiological, biochemical, physical, and microbiological processes. Value-addition interventions are most effective when they target these drivers directly rather than applying generic preservation measures that ignore commodity physiology and supply-chain conditions. This is particularly evident in tropical root and tuber crops such as cassava, where deterioration after harvest is closely associated with tissue injury, oxidative responses, microbial invasion, and storage temperature (Saravanan *et al.,* 2016; Saravanan *et al.,* 2020; More *et al.,* 2019).

The major deterioration drivers can be grouped into five linked processes. First, harvested produce remains metabolically active; respiration consumes sugars and organic acids, releases CO_2, water, and heat, and accelerates senescence, firmness loss, and flavour change. In climacteric fruits such as mango and banana, ethylene-mediated ripening further narrows the handling window by promoting softening, colour development, aroma formation, and greater susceptibility to decay. Second, transpiration-driven water loss causes wilting, shrivelling, turgor decline, texture weakening, and visual downgrade, particularly in vegetables and fruits stored under low relative humidity or unsuitable packaging. Third, cutting, peeling, bruising, and other injuries disrupt cellular compartmentation and promote enzymatic browning through contact between phenolic substrates and oxidative enzymes, especially polyphenol oxidase.

Pigment instability is also influenced by oxygen, pH, temperature, and antioxidant status, making browning control essential in fresh-cut and minimally processed products. Fourth, microbial spoilage is intensified by tissue injury, condensation, nutrient leakage, storage duration, and poor sanitation. Fungal decay and bacterial soft rots dominate in whole produce, while minimally processed products carry higher safety risks because natural barriers are removed and nutrient-rich surfaces are exposed. Fifth, mechanical injury during harvesting, grading, packing, and transport accelerates respiration, ethylene production, membrane damage, and pathogen entry, making supply-chain handling a direct determinant of physiological stability and market value.

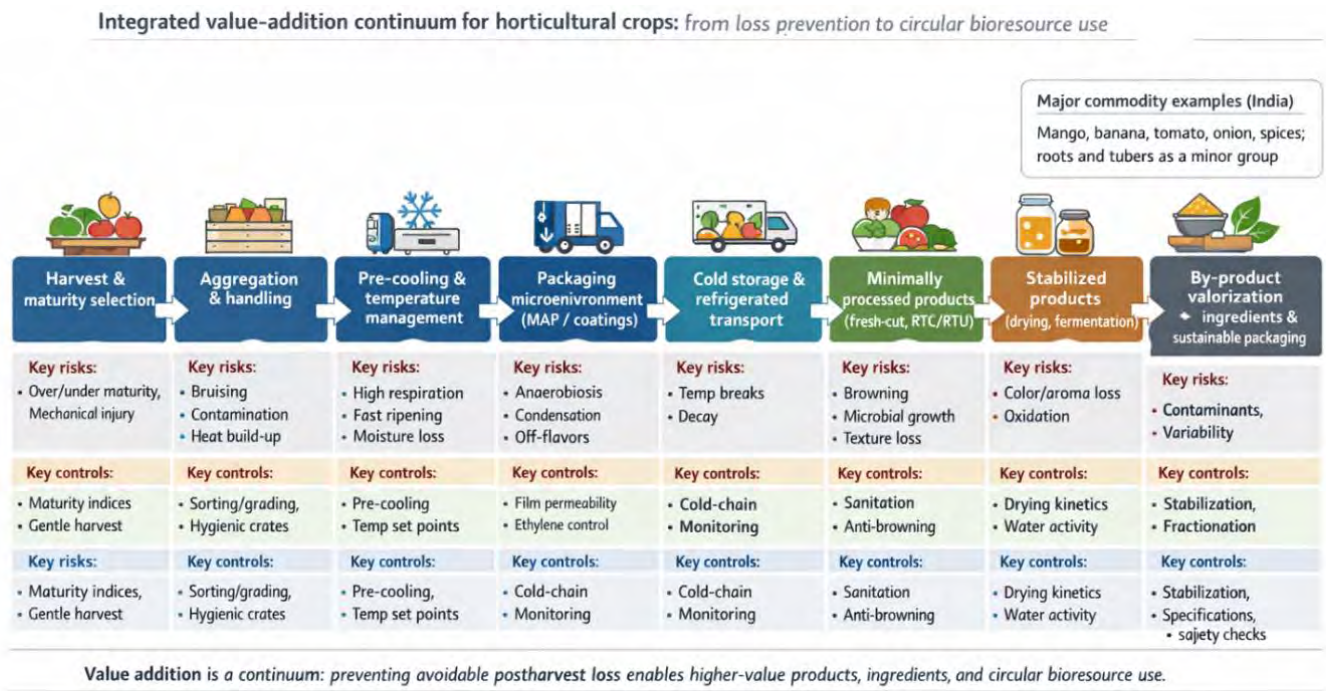


Fig. 1: Integrated value-addition continuum for Indian horticultural crops: from loss prevention to circular bioresource use

These mechanisms explain why shelf-life extension depends on integrated rather than isolated interventions. Temperature and humidity management slow respiration and water loss; modified atmospheres, edible coatings, and semi-permeable packaging regulate gas exchange and moisture movement; anti-browning dips, sanitation, and clean-label antimicrobials reduce quality loss and microbial risk; and cushioning, stack-load control, and package design limit mechanical injury. However, each intervention must be matched to commodity physiology and storage conditions. Coatings or films that are too restrictive may induce anaerobic metabolism and off-flavours, whereas poorly controlled smart or active packaging may add cost without improving operational decisions (Alemu *et al.,* 2025; Du *et al.,* 2025; Moradinezhad *et al.,* 2025). Therefore, the mechanistic foundation of value addition lies in selecting technology bundles that jointly manage respiration, ripening, moisture loss, browning, microbial spoilage, and handling stress under realistic supply-chain conditions.

Postharvest quality retention as first stage of value-addition

Value- addition in horticulture begins with preserving the biological and physical integrity of produce so that it reaches markets or processors with an acceptable grade, firmness, colour, and safety. In India, where temperature breaks, delayed movement, and handling stress are common, the most cost-effective gains often come from slowing deterioration rather than from complex downstream processing. Across commodities, the core principles are similar: remove field heat rapidly, maintain suitable temperature and relative humidity, minimise mechanical damage, and create a stable microenvironment through packaging and atmosphere management matched to the respiration and transpiration behaviour of the produce.

The postharvest behaviour of mango, banana, tomato, and onion is strongly influenced by harvest maturity and preharvest conditions, which affect firmness, flavour potential, and storage life. Harvesting too early can impair ripening uniformity and eating quality, whereas a late harvest reduces firmness and transportability. Maturity indexing is, therefore, a practical control point because even advanced coatings or packaging cannot compensate for poor initial physiological quality. Rapid pre-cooling is another critical step, as it lowers respiration, ethylene production, and moisture loss. Its performance can be improved through commodity- and package-specific optimisation of airflow, vent design, and heat transfer, showing that pre-cooling should be viewed as a heat- and mass-transfer problem linked to packaging geometry and commodity physiology rather than simply as a choice of method (Kumar *et al.,* 2023).

Cold storage remains the most effective shelf-life extension tool, but the cold chain depends on continuity from harvest to retail rather than on storage alone. Common failures include non-uniform cooling, high energy demand, and weak control, which can cause uneven ripening and localised spoilage, especially in climacteric fruits and mixed loads (Hoffmann *et al.,* 2025). Under Indian conditions, the key operational priorities are commodity-specific temperature set points, relative humidity management to reduce shrivel and weight loss, and effective monitoring, since breakdowns often result from variability within storage systems rather than from nominal set points.

Packaging and atmosphere management function as microenvironment engineering. Modified atmosphere packaging (MAP) depends on balancing produce respiration with film permeability so that O_2 consumption, CO_2 production, and gas transmission remain compatible (Caleb *et al.,* 2013). It is useful for both whole and minimally processed produce and can be strengthened by edible coatings used as complementary barrier systems (Zdulski *et al.,* 2024). However, failure can occur due to a film–commodity mismatch, condensation, or unstable temperature control, leading to anaerobiosis, off-flavours, and microbial growth. Where uninterrupted cold-chain continuity is not possible, low-energy options such as evaporative cooling can still improve quality retention at aggregation points by lowering temperature and increasing relative humidity (Basediya *et al.,* 2013).

Mechanical injury control is equally important because bruising and compression damage accelerate respiration, ethylene evolution, membrane leakage, and pathogen entry. This is especially critical in bulk handling of tomato and banana, and in mango, where surface injury and lenticel damage reduce market grade. Packaging design, therefore, affects not only transport but also cooling efficiency, humidity management, and injury risk, with ventilation geometry influencing both pre-cooling performance and produce stability (Cao *et al.,* 2020).

Quality retention must ultimately be measured in terms that reflect economic value and consumer acceptance, including firmness, colour, flavour balance, weight loss, decay incidence, and sensory shelf life. For tropical tuber crops, physiological quality retention is especially important because deterioration often begins soon after harvest and directly affects marketability, processing suitability, and shelf life (Raju, 2023; Saravanan *et al.,* 2020). The relative importance of these endpoints varies with the intended value pathway:

fresh-market mango depends heavily on appearance and firmness, whereas processing tomato may prioritise soluble solids and microbial quality. Recognising such endpoint differences helps connect postharvest science to practical value addition.

Clean-label and low-residue postharvest technologies (coatings, naturals, sanitisation, non-thermal)

Clean-label postharvest technologies aim to extend shelf life while reducing reliance on conventional chemical residues and preserving sensory, nutritional, and physiological quality. They include edible or biodegradable barrier systems, natural antimicrobials and antioxidants, and physical or non-thermal sanitation methods. Their value lies in combining microbial control with quality retention, safety, sensory acceptability, and operational feasibility.

Edible coatings are among the most widely studied interventions because they act as semi-permeable barriers to moisture and gas exchange and can also deliver active compounds. Polysaccharide-, protein-, and lipid-based coatings can reduce respiration, dehydration, and microbial growth when their permeability and application method are matched to the commodity and storage environment (Alemu *et al.,* 2025). Natural antimicrobials such as essential oils, phenolic-rich extracts, organic acids, and chitosan are increasingly incorporated into coatings and packaging systems, but their use depends on formulation stability, release behaviour, extract variability, and sensory acceptability (Aljabary *et al.,* 2025).

For fresh-cut and minimally processed products, sanitation remains a primary safety control point. Alternatives to chlorine-based systems include ozone, UV-C, cold plasma, pulsed light, ultrasound, micro- and nanobubbles, and electrolysed water (Jin and Adhikari, 2025). Their effectiveness depends on commodity sensitivity, surface characteristics, organic load, water quality, treatment uniformity, and line conditions. Electrolysed water is particularly relevant for packhouse and MSME settings because it combines antimicrobial activity with operational flexibility, although adoption requires control of pH, oxidation–reduction potential, dosing, organic load, equipment maintenance, and worker safety (Bulantekin *et al.,* 2026; Giametta *et al.,* 2025). Non-thermal interventions such as UV-C, ozonation, and cold atmospheric plasma reduce residue concerns and avoid heat damage, but their performance is constrained by surface irregularity, shadowing, limited penetration, uneven exposure, and possible surface injury if treatment intensity is not optimised (White *et al.,* 2025).

The major clean-label postharvest technologies in terms of mechanism, commodity fit, constraints, and minimum validation endpoints are given in Table 1. Overall, these technologies are complementary rather than interchangeable. Edible coatings are most useful where moisture loss, browning, and moderate respiration control are major constraints, whereas MAP is more suitable when package-atmosphere regulation is required, provided film permeability is matched to commodity respiration and storage temperature. Electrolysed water, UV-C, ozone, and cold plasma primarily serve as sanitation tools and must be integrated with hygienic handling, cooling, and appropriate packaging. Under Indian supply-chain conditions, the practical priority is to design commodity- and scale-specific technology bundles rather than promote any single preservation method: climacteric fruits require careful handling, ripening management, cooling, and compatible packaging; fresh-cut products require validated sanitation, refrigeration, and MAP or coatings; and onion and spices often benefit more from dehydration, moisture control, and high-barrier packaging.

Value-addition through minimally processed and convenience products: fresh-cut, RTC/RTU, dehydration, and fermentation

Convenience-oriented horticultural products, including fresh-cut, ready-to-cook (RTC), ready-to-use/ready-to-eat (RTU/RTE), dehydrated, and fermented products, are important value-addition routes because they convert biological perishability into consumer utility. However, they also shift the main constraints from whole-produce physiology to tissue injury, enzymatic browning, microbial safety, mass transfer, and packaging–cold chain performance. Compared with intact produce, minimally processed products generally have shorter and more safety-sensitive shelf life, requiring simultaneous control of multiple deterioration drivers.

Fresh-cut produce deteriorates rapidly because peeling, slicing, shredding, and trimming expose internal tissues, disrupt cellular compartmentation, increase respiration, stimulate wound-induced phenolic metabolism, and create nutrient-rich surfaces for microbial growth. Even under refrigeration, the shelf life of many minimally processed vegetables is often about a week, depending on commodity and handling practices (Villanova-Estors *et al.,* 2025). Fresh-cut value addition should therefore combine hygienic design, rapid cooling, atmosphere and moisture management, and targeted anti-browning and antimicrobial hurdles. Coatings and modified atmosphere packaging (MAP) are useful complementary tools because coatings

Table 1: Clean-label postharvest technologies: mechanism, best-fit commodities, and key *limitations*

Technology	Primary mechanism	Best-fit commodity / product type	Main constraints / failure modes	Validation endpoints to report (minimum set)
Edible coatings (polysaccharide/protein/ lipid; sometimes with bioactives)	Semi-permeable barrier to O_2/CO_2 and water vapor; can deliver antimicrobials/ antioxidants	Whole fruits (mango, banana), selected vegetables; fresh-cut (as secondary barrier)	Anaerobiosis/off-flavours if too restrictive; condensation risk; coating uniformity; sensory changes; scale-up of application/drying	Shelf-life gain (days), weight loss (%), firmness (N), colour change (ΔE), respiration/ethylene trends (if available), decay incidence (%)
Natural antimicrobials (plant extracts, essential oils, chitosan, organic acids)	Antimicrobial action via membrane disruption, pH effects, phenolic interactions; antioxidant support	Fresh-cut/RTC produce (with sensory care), decay-prone fruits, active packaging additives; spices (natural synergy)	Sensory taint (essential oils), volatility, variability in composition, regulatory/ standardization, inconsistent efficacy with high organic load	Microbial log reduction, sensory acceptability, decay incidence, residue/taint assessment, stability over storage
Electrolysed water (acidic/ neutral)	Oxidative inactivation (HOCl/ORP-driven), reduces surface microbial load with limited chemical residues	Fresh produce wash lines, fresh-cut/RTC pre-treatment; packhouse sanitation	Water quality dependence, dosing control, organic load reduces efficacy, worker safety, equipment costs/ maintenance	Log reduction, cross-contamination control, quality retention (colour/ firmness), ORP/pH/free chlorine equivalents, water reuse performance
Cold plasma / UV-C / ozone (non-thermal sanitization)	Reactive species or UV damage to microbial DNA/ membranes; surface decontamination	Fresh-cut/RTC, high-risk surfaces; some fruits/ vegetables where surface treatment is feasible	Shadowing/uneven exposure, limited penetration, potential surface injury or accelerated senescence, equipment cost/line integration	Log reduction, quality changes (colour/texture), shelf-life gain, treatment uniformity metrics, safety/ operational parameters
Modified atmosphere packaging (MAP; passive or controlled)	Gas balance (lower O_2, higher CO_2) slows respiration and microbial growth; moisture management	Whole fruits/vegetables, fresh-cut packs, RTC mixes	Film–commodity mismatch → anaerobiosis/off-flavours; condensation and decay; temperature breaks destabilize atmosphere	Headspace O_2/CO_2 profiles, shelf-life gain, sensory acceptance, decay incidence, weight loss, browning index (fresh-cut)

reduce oxygen ingress and moisture loss, while MAP stabilises the O_2/CO_2 environment, thereby slowing browning and senescence-linked quality loss when properly designed (Zdulski *et al.,* 2024). Sanitisation options now extend beyond chlorine to non-thermal and low-residue approaches, although their practical value depends on commodity sensitivity, surface characteristics, water quality, and line conditions (Jin and Adhikari, 2025).

The RTC and RTU products, such as vegetable mixes, peeled onion, tomato preparation bases, and spice-based mixes, add value by reducing preparation time and creating outlets for processing-grade produce. Since many remain intermediate between fresh and fully shelf-stable products, their stability depends on water activity, moisture migration, microbial management, packaging atmosphere, condensation control, and cold-chain continuity (Mathew and Sharma, 2023).

Dehydration and intermediate-moisture products remain robust value-addition pathways for onion flakes and powders, tomato powders, dried vegetables, spice products, and fruit leathers or chips. Their main technical goals are to preserve colour, aroma, bioactives, texture, and rehydration quality while reducing energy use and thermal damage. Advanced and hybrid drying systems, including electromagnetic-assisted approaches, are gaining attention because they can improve drying efficiency and quality retention when optimised (Mohammed *et al.,* 2024).

Fermentation provides another stabilisation route through acidification and antimicrobial metabolite production, while also modifying flavour, functionality, and digestibility. Fermentation outcomes depend on substrate chemistry, salt or sugar regime, starter culture, and process control; therefore, functional or probiotic claims should be supported by strain-level and safety evidence rather than assumed (Gangakhedkar *et al.,* 2025; Wei *et al.,* 2025).

Across major Indian crops, fresh-cut mango and banana require rapid cooling, browning control, and carefully designed coatings or MAP; tomato is well suited to preparation bases, dehydration, sauces, and pastes; onion is particularly suited to dehydration and peel valorisation; and spices depend on drying and storage practices that preserve aroma, colour, and safety. Roots and tubers fit this framework mainly through RTC formats, dehydration, flour, starch, and related value-added ingredients. Cassava-based products illustrate how processing can convert highly perishable roots and related biomass into more stable starch-, flour-, and value-added food ingredients (Zhang *et al.,* 2025; Krishnakumar *et al.,* 2020; Hasmi *et al.,* 2025).

Byproduct valorisation and circular bioresource use: functional ingredients, pigments, fibre/pectin, and links to sustainable packaging

Byproduct valorisation is an important component of horticultural value addition because processing of mango, banana, tomato, onion, spices, and root crops generates substantial quantities of peels, pomace, seeds, kernels, trimmings, and spent biomass. These residues contain recoverable fractions such as dietary fibre, pectin and related polysaccharides, phenolics, pigments, essential-oil residues, starch, and, in some cases, proteins. The emphasis is shifting from broad waste-utilisation claims to biorefinery-style approaches in which residues are segregated, stabilised, fractionated, and standardised for defined functional, safety, storage, and regulatory targets. Figure 2 illustrates this circular valorisation pathway by linking horticultural by-product streams with recoverable fractions, functional properties, and potential food, packaging, and non-food applications.

Residue composition depends on crop type, cultivar, maturity, season, and processing chain. Mango provides peel and kernel fractions, tomato generates pigment- and fibre-rich pomace, onion produces flavonoid-rich peel and trimmings, banana contributes peel and sometimes pseudo-stem biomass, while spice processing leaves spent residues after oleoresin or essential-oil extraction. Across these streams, valorisation is strongest when materials are separated early, microbial contamination is minimised, and recovery targets are defined by measurable specifications rather than general labels such as "antioxidant extract." Fibre-rich fractions are among the most scalable because they can serve as bulking agents, texture modifiers, fat replacers, or potential prebiotic ingredients, provided particle size, sensory neutrality, and contaminant control are standardised. Protein recovery from fruit and vegetable by-products is promising, but remains limited by matrix complexity, extraction selectivity, and functionality in final formulations (Khalid *et al.,* 2025).

Natural colourants and phenolic-rich extracts are high-value targets, particularly where residues contain carotenoids, anthocyanins, flavonoids, or other bioactive compounds. Tomato pomace is relevant for carotenoids and lycopene, while onion peel is a notable source of quercetin and related flavonoids. However, pigment value depends not only on extraction yield but also on stability against light, oxygen, pH, and temperature, as well as performance in the final application. Advanced extraction and encapsulation methods are therefore important for improving pigment stability and functionality (Ramzan *et al.,* 2025; Ayub *et al.,* 2026; Sahu *et al.,* 2025).

Pectin and related polysaccharides provide a strong link between residue valorisation and sustainable packaging because they function as gelling, stabilising, film-forming, and coating materials. Their usefulness depends on extraction chemistry and structural traits such as degree of esterification, galacturonic acid content, molecular weight, and gel strength. Thus, extraction–structure–function relationships are more informative than simple yield comparisons and should guide the development of edible films, coatings, and biodegradable packaging materials (Akhter *et al.,* 2024).

Packaging is one of the clearest bridges between circular bioresource use and postharvest quality retention. Horticultural residues may serve as polymer matrices, such as pectin- or fibre-rich fractions, or as active additives, including phenolic and pigment extracts with antioxidant, antimicrobial, or UV-blocking properties. In cassava, stem biomass has also been explored as a potential industrial starch source, showing that residue valorisation can extend beyond fruit peels and pomace to structurally different crop by-products (Hasmi *et al.,* 2025). Mango peel extracts and spice-derived bioactives are increasingly discussed in active packaging systems, while biodegradable and smart films based on renewable biopolymers continue to advance through additives that improve barrier and mechanical performance (Fang *et al.,* 2025; Kumar *et al.,* 2025; Singh *et al.,* 2025; Zhang *et al.,* 2025).

A mature valorisation strategy must remain safety-led and specification-driven. Microbial loads often require stabilisation; solvent and contaminant compliance must be ensured; and phenolic-rich extracts may introduce bitterness, astringency, or colour changes. Regulatory acceptance is also critical when residue-derived fractions are intended for food, nutraceutical, or packaging applications. Therefore, by-product valorisation should be supported by toxicological evidence, quality assurance, functional validation, and techno-economic assessment rather than by circular-economy rhetoric alone (Tsegay *et al.,* 2025).

Smart, active, and sustainable packaging for horticultural value-addition (fresh chains and minimally processed products)

Packaging is now an enabling technology for horticultural value addition rather than a passive container. Modern systems regulate the produce microenvironment through O_2/CO_2 exchange, water-vapour movement, active antimicrobial or antioxidant

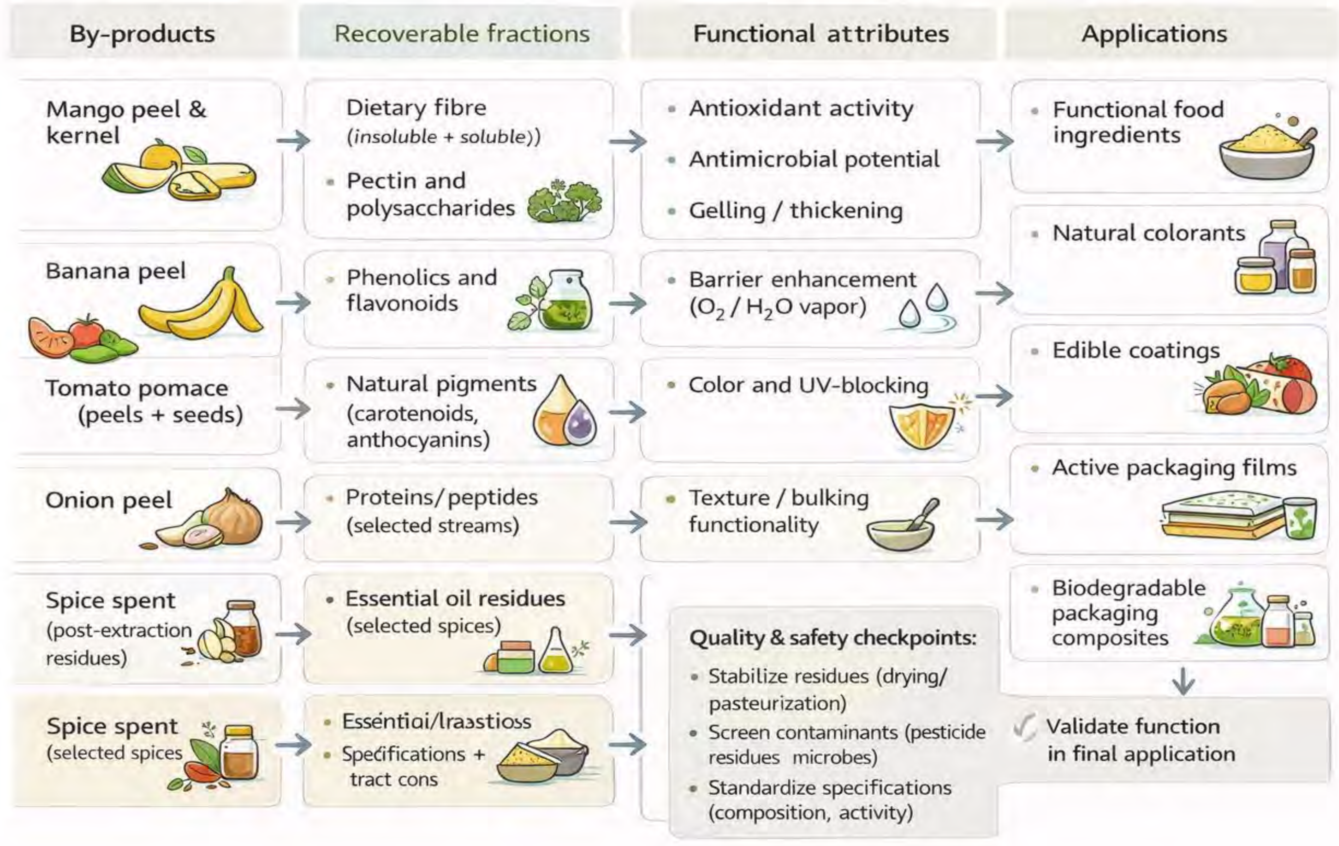


Fig. 2: Circular valorization pipeline: horticultural byproducts → fractions → fractions → applications

functions, and freshness monitoring. This is especially relevant in India, where long transport distances, uneven cold-chain continuity, repeated handling, and increasing pressure to reduce conventional plastics affect both quality retention and packaging choices.

Smart packaging includes time–temperature indicators, gas sensors for O_2, CO_2, and ethylene, freshness indicators based on pH-sensitive dyes or volatile metabolites, and biosensors linked to microbial activity. Their main value lies in risk management: they make hidden quality loss visible and can support sorting, routing, retail decisions, and shelf-life prediction. In horticultural chains, the most useful data streams are temperature history, humidity, and headspace gas trends because temperature abuse accelerates respiration, ripening, and microbial growth, while poor humidity and gas control can promote condensation, decay, anaerobiosis, and off-flavours.

Active packaging extends shelf life by interacting with the food environment through antimicrobial activity, antioxidant protection, gas scavenging or regulation, ethylene control, and moisture management. Biopolymer matrices based on polysaccharides and proteins are increasingly used as carriers for these functions because they align with sustainability goals and consumer preferences. However, their effectiveness depends on release behaviour, sensory neutrality, migration safety, and compatibility with the target commodity.

Edible films, hydrogel films, and biodegradable biopolymer materials should be treated as tunable systems rather than simple plastic substitutes. Their value depends on how material properties translate into quality outcomes: water-vapour permeability affects moisture retention and condensation risk; O_2/CO_2 permeability determines whether respiration is safely moderated or shifted toward anaerobiosis; and mechanical strength influences handling performance. Carbohydrate-based films from starch, cellulose, chitosan, pectin, alginate, or pullulan are promising, but many still have weak moisture barriers and poor stability under humid conditions, creating a need for blends, additives, and nanocomposites.

A major limitation is that packaging is often evaluated in isolation rather than matched to commodity physiology. High-respiration climacteric fruits such as mango and banana require adequate gas permeability and ethylene-responsive strategies, while fresh-cut and moisture-sensitive vegetables need condensation control, antimicrobial support, and reliable cooling. For spices and dehydrated products, packaging performance depends mainly on moisture exclusion, aroma retention, oxidation control, and mycotoxin risk reduction rather than respiration management.

For Indian supply chains, adoption will depend on unit cost, compatibility with existing crates and vented boxes, ease of interpreting indicators, performance under humid distribution conditions, regulatory acceptance of active compounds, and migration safety of additives. Smart, active, and sustainable packaging systems are most valuable when linked to specific operational decisions such as sorting, rerouting, shelf-life estimation, and waste reduction.

Commodity-wise synthesis for major Indian horticultural crops

A commodity-wise synthesis is most useful when it links dominant deterioration mechanisms with feasible value-addition routes and technology bundles. Table 2 summarises these relationships for major Indian horticultural commodities across physiological, microbial, mechanical, and processing dimensions.

Mango and banana, as climacteric fruits, require interventions that regulate ripening while preventing injury, moisture loss, and decay. The priority is an integrated bundle of maturity-based harvesting, careful handling, cooling, humidity management, ripening control, and packaging that cushions fruit while allowing adequate gas exchange. Fresh-cut mango and banana products require stricter control of browning, sanitation, and refrigeration.

Tomato value loss is driven mainly by mechanical injury, softening, water loss, and microbial spoilage, especially during ambient transport and retail handling. Gentle handling, rapid cooling, condensation control, and suitable packaging are therefore central. Fresh-cut and RTC tomato products require validated sanitation and refrigeration, whereas dehydration, sauces, pastes, and

Table 2: Major Indian horticultural commodities: dominant postharvest loss drivers and priority value-addition routes

Commodity group (examples)	Dominant loss drivers (physiological / microbial / mechanical)	Most sensitive stage (farm → aggregation → transport → retail)	Priority intervention(s) (science-led)	Priority value-added products / routes
Mango, banana (climacteric fruits)	Physiological: high respiration, ethylene-driven ripening, softening; Microbial: anthracnose/stem-end rot (latent infections); Mechanical: bruising, compression damage	Aggregation & handling; transport; retail (ripening window)	Rapid field heat removal (pre-cooling where feasible), temperature–RH management, ripening management (uniformity), cushioning + pack design to reduce bruising, packaging permeability matching (MAP/coatings), hygiene to reduce decay	Fresh-cut (limited, high control), RTC fruit pieces (strict cold chain), pulps/purees/nectars, dehydrated slices/leathers, fermentation-based beverages (where relevant), by-product capture (peel/kernel ingredients)
Tomato (soft, high-water vegetable fruit)	Physiological: rapid softening, water loss; Microbial: bacterial soft rot/fungal decay; Mechanical: bruising, cracking during handling/stacking	Transport; retail (temperature abuse); aggregation for grading	Gentle handling and stack-load management, rapid cooling priority, condensation control, MAP/coatings where suitable, sanitation for RTC/fresh-cut lines, cold-chain continuity + monitoring	RTC bases (chopped/peeled, puree), fresh-cut mixes (strict sanitation), dehydration (powder/flakes), sauces/pastes, fermentation (limited; niche), pomace valorization (pigments/fibre)
Onion (storage organ/bulb crop)	Physiological: sprouting, weight loss, dormancy break; Microbial: storage rots; Mechanical: neck/tissue damage accelerating rot	Farm/curing; storage period; transport (bulk injury)	Proper curing (neck drying, surface drying), ventilated storage basics, temperature/RH optimization for storage, sorting to remove damaged bulbs, dehydration for stabilization, improved packaging for dried products	Dehydration (flakes/powder), paste/condiments, minimally processed peeled onion (short shelf life), by-product valorization (peels → flavonoids/extracts)
Spices (turmeric, chilli, pepper, etc.)	Physiological: quality decline mainly via oxidation and aroma loss (not senescence); Microbial/toxin: molds, mycotoxin risk when moisture is high; Mechanical: contamination and breakage during drying/handling	Drying stage; storage; retail (moisture re-entry)	Drying kinetics optimization to safe moisture/water activity, avoid re-wetting, high moisture-barrier packaging, oxygen/oxidation control, clean storage, monitoring of water activity, mycotoxin risk management protocols	Dried whole spices, powders, oleoresins/essential oils (industrial), blended spice mixes (RTC/RTU), fermentation/pickling in niche products, spice spent valorization (active packaging additives)
Others (examples: grapes/citrus/guava; leafy vegetables; floriculture produce)	Fruits: physiological (senescence, dehydration), microbial decay; Leafy veg: rapid water loss + microbes; Flowers: dehydration and senescence; Mechanical injury common	Leafy veg: transport & retail; Fruits: aggregation/transport; Flowers: transport/retail	Leafy veg: rapid cooling + high RH, hygienic handling, packaging for moisture control; Fruits: temperature set points + MAP/coatings; Flowers: hydration solutions, cooling, packaging to reduce dehydration	Fresh-cut salad/leafy mixes, minimally processed packs, juices/pulp, dehydration, fermentation products (pickles), edible coatings for shelf-life extension

intermediate-moisture products provide more robust options where cold-chain continuity is weak.

Onion requires a different approach because losses are dominated by sprouting, rotting, physiological weight loss, and storage-linked price volatility. Proper curing, sorting, ventilated storage, and humidity management are therefore more important than respiration control. Dehydration into flakes and powder remains a strong value-addition route, while onion peel offers potential for flavonoid-rich extract applications.

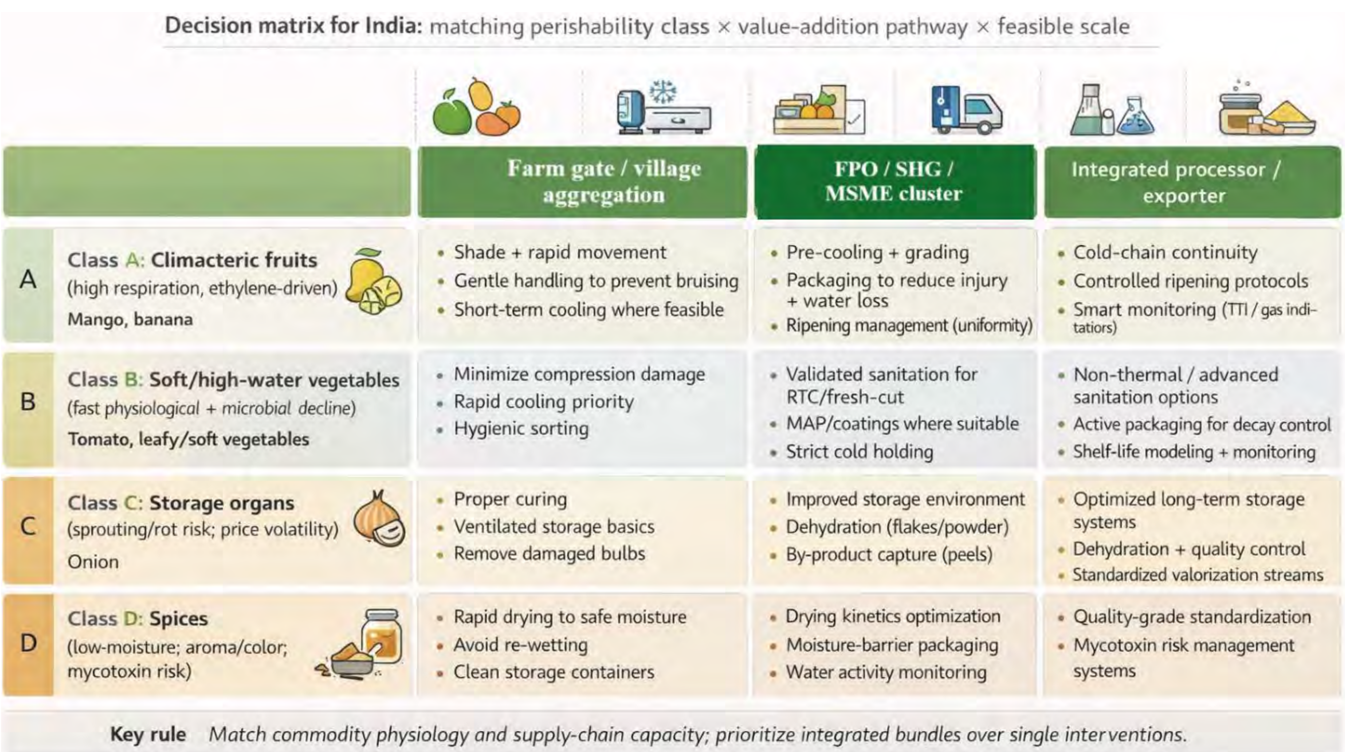
Spices are governed mainly by drying efficiency, safe moisture levels, aroma and colour retention, oxidation control, and prevention of fungal contamination or mycotoxin risk. Drying kinetics, water activity management, clean storage, and high-barrier packaging are therefore central to quality assurance. Spice-derived bioactives may also support natural preservation and active packaging when sensory effects, stability, and dosage are controlled.

Roots and tubers contribute to value addition through RTC formats, dehydration, flour production, starch- or fibre-based ingredients, and selected biodegradable material applications. In cassava, the rapid onset of postharvest physiological deterioration makes timely processing, storage-temperature management, and conversion into stable starch- or flour-based products especially important (Saravanan *et al.*, 2016; Saravanan *et al.*, 2020; Raju, 2023).

Integration framework: matching crop perishability × technology × scale.

An India-relevant value-addition framework should treat horticultural chains as combinations of commodity perishability and operational scale. The same intervention, such as modified atmosphere packaging, edible coatings, or non-thermal sanitisation, can perform very differently depending on crop physiology, time to market, temperature continuity, hygiene, and organisational capacity. Therefore, technology selection should be based on feasible bundles rather than isolated tools.

A practical matching logic can be built around two axes. The first is perishability class: high-respiration climacteric fruits such as mango and banana; high-water vegetables such as tomato and leafy or soft vegetables; storage organs such as onion, where sprouting, rotting, and price volatility interact; and low-moisture, high-value commodities such as spices, where aroma, colour, oxidation, and mycotoxin risk are critical. The second axis is scale: farm gate or village aggregation with limited equipment; FPO/SHG/MSME clusters with basic packhouse and processing capacity; and integrated processors or exporters with quality assurance, cold-chain continuity, and advanced preservation options.



Decision matrix for India: matching perishability class × value-addition pathway × feasible scale

	Farm gate / village aggregation	FPO / SHG / MSME cluster	Integrated processor / exporter
A — Class A: Climacteric fruits (high respiration, ethylene-driven) Mango, banana	• Shade + rapid movement • Gentle handling to prevent bruising • Short-term cooling where feasible	• Pre-cooling + grading • Packaging to reduce injury + water loss • Ripening management (uniformity)	• Cold-chain continuity • Controlled ripening protocols • Smart monitoring (TTI / gas indi-tatiors)
B — Class B: Soft/high-water vegetables (fast physiological + microbial decline) Tomato, leafy/soft vegetables	• Minimize compression damage • Rapid cooling priority • Hygienic sorting	• Validated sanitation for RTC/fresh-cut • MAP/coatings where suitable • Strict cold holding	• Non-thermal / advanced sanitation options • Active packaging for decay control • Shelf-life modeling + monitoring
C — Class C: Storage organs (sprouting/rot risk; price volatility) Onion	• Proper curing • Ventilated storage basics • Remove damaged bulbs	• Improved storage environment • Dehydration (flakes/powder) • By-product capture (peels)	• Optimized long-term storage systems • Dehydration + quality control • Standardized valorization streams
D — Class D: Spices (low-moisture; aroma/color; mycotoxin risk)	• Rapid drying to safe moisture • Avoid re-wetting • Clean storage containers	• Drying kinetics optimization • Moisture-barrier packaging • Water activity monitoring	• Quality-grade standardization • Mycotoxin risk management systems

Key rule *Match commodity physiology and supply-chain capacity; prioritize integrated bundles over single interventions.*

Fig. 3: Decision matrix for India: matching perishability class × value-addition pathway × feasible scale

As presented in Figure 3, the proposed decision matrix links crop perishability class with feasible value-addition pathways and operational scale under Indian conditions.

At farm-gate or village level, the priority is to slow immediate deterioration through careful handling, shading, simple grading, rapid field-heat removal, and low-energy cooling where feasible. At the FPO/SHG/MSME level, the focus shifts to predictable marketable life and basic processing stability through packhouse hygiene, short cold holding, validated sanitation, realistic MAP or coating use, dehydration, and by-product capture. At the integrated processor or exporter scale, continuous cold-chain management, controlled ripening, advanced sanitation, smart or active packaging, and systematic residue biorefinery approaches become more feasible.

Policy and investment support should reinforce continuity across pre-cooling, grading, packing, cold storage, transport, processing, and marketing because value addition in perishables depends on chain integrity rather than standalone equipment. The framework can be applied by classifying the commodity by dominant loss driver, identifying realistic infrastructure constraints, selecting a technology bundle, and evaluating performance through measurable endpoints such as shelf-life extension, weight loss, decay incidence, firmness, colour retention, safety indicators, and economic return.

Research gaps and future thrust areas (2026–2031)

Available evidence should be translated into a focused research agenda for Indian horticultural value chains, with emphasis on scalability, field-level validation, and economic feasibility. Table 3 summarises the major research gaps and future thrust areas for Indian horticultural value addition during 2026–2031.

Commodity-specific shelf-life prediction remains underdeveloped. Many studies report shelf-life extension without models that integrate temperature exposure, relative humidity, packaging atmosphere, microbial risk, and real supply-chain variability. Predictive models validated under Indian distribution conditions would support better routing, inventory decisions, technology comparison, and market planning. Packaging–produce matching also needs standardisation because poorly selected films or coatings can cause anaerobiosis, off-flavours, condensation, and decay. Future research should define practical permeability design windows for mango, banana, tomato, and common fresh-cut products under realistic storage temperatures.

Clean-label sanitation and cooling technologies require field-level validation. Laboratory performance of electrolysed water, UV-C, ozone, cold plasma, and related methods often declines under packhouse and MSME conditions due to organic load, uneven surfaces, variable water quality, shadowing, and line-speed constraints. Trials should therefore include microbial reduction, quality retention, water reuse, worker safety, cost endpoints, and comparison with existing practices. Similarly, research on low-energy pre-cooling, short-term cooling at aggregation points, and packaging designs that improve cooling efficiency should be assessed

Table 3: Research gaps and future thrusts for Indian horticultural value addition (2026–2031)

Gap theme	What is missing now	Proposed research direction	Expected outcome / impact
Predictive shelf-life models	Few commodity-specific predictive models validated under Indian temperature breaks and mixed logistics	Build models combining physiology + microbial risk + packaging, trained/validated with real chain temperature–RH data	Reliable shelf-life prediction; reduced waste; better routing/marketing decisions
Packaging–produce matching	Permeability selection is often ad hoc; frequent failures via anaerobiosis/condensation	Develop permeability "design windows" for major commodities and fresh-cut packs at realistic temperatures	Fewer packaging failures; measurable shelf-life gain; improved sensory quality
Sanitation scale-up for fresh-cut/RTC	Lab efficacy does not translate well to packhouse/MSME lines with high organic load and variable water quality	Near-industrial validation trials of electrolyzed water/non-thermal systems with SOPs for dosing, water reuse, and hygiene	Safer RTC/fresh-cut products; reproducible microbial control; higher consumer trust
Cold-chain continuity & energy efficiency	Non-uniform cooling and intermittent refrigeration remain dominant loss drivers	Engineer low-energy pre-cooling/short-term cooling and monitoring solutions for aggregation points	Loss reduction at early stages; improved grade retention; longer market window
By-product standardization	Valorization often lacks specifications, contaminant screening, and functional validation in end products	Create "specification-led" residue valorization pipelines (stabilization → screening → fraction specs → application testing)	New ingredient streams; scalable circular economy products; regulatory-ready extracts
Spices: drying–storage–mycotoxin systems	Drying, packaging, and mycotoxin risk are studied separately; integrated risk management is limited	Systems studies linking drying kinetics, water activity, packaging barrier performance, and mycotoxin monitoring	Reduced contamination risk; improved export/quality compliance; stable aroma/color retention
FPO/MSME operational models	Technology adoption fails due to weak SOPs, QA, maintenance, and market linkage design	Develop operational playbooks (SOPs, QA templates, maintenance plans) and evaluate performance in pilot clusters	Higher adoption success; improved farmer price realization; scalable decentralised value addition

through verified shelf-life extension, grade retention, and measurable loss reduction.

Byproduct valorisation must shift from broad antioxidant claims to specification-led and safety-led pathways. Future work should establish residue stabilisation protocols, contaminant screening, regulatory readiness, and extraction-to-function specifications such as pectin degree of esterification, fibre particle size, pigment stability, and bioactive performance in end-use applications. Techno-economic evaluation is essential to distinguish feasible MSME-scale value streams from laboratory demonstrations. For tropical root and tuber crops, research should also define practical shelf-life thresholds, storage-temperature responses, and processing windows that link physiological deterioration with product quality and industrial suitability (Raju, 2023; Saravanan *et al.,* 2020; Hasmi *et al.,* 2025).

Spices require integrated drying–storage–packaging research because aroma loss, colour deterioration, moisture re-entry, oxidation, and mycotoxin risk are interlinked. Systems studies should connect drying kinetics, water activity targets, packaging barrier performance, and rapid diagnostics for trader and storage environments. Decentralised value addition also needs operational research on FPO-led packhouses and micro-processing units, including SOPs, quality assurance templates, maintenance systems, skill requirements, and market linkages.

A practical five-year roadmap can therefore focus on four priorities: improving cold-chain continuity and packaging–produce matching for mango, banana, and tomato; developing MSME-ready sanitation and dehydration systems for onion and spices; standardising byproduct ingredients and bioactive packaging additives with safety assurance; and embedding digital monitoring and predictive shelf-life tools into procurement, logistics, and retail decisions.

CONCLUSION

Value- addition in Indian horticulture is best understood as a continuum that begins with preventing avoidable postharvest losses and extends to producing stable, higher-value products, ingredients, and packaging materials. Deterioration is driven by interacting processes, including respiration and ripening, water loss and texture decline, browning and pigment instability, and microbial spoilage intensified by injury and temperature abuse.

Packaging has become a central postharvest technology. Smart and active systems can support freshness monitoring, reduce oxidative and microbial deterioration, and improve risk management where cold-chain continuity is uneven. Convenience products such as fresh-cut and RTC/RTU formats offer clear value potential for mango, banana, tomato, and onion, but they require strict hygiene, rapid cooling, and well-matched MAP or coating systems. Dehydration and fermentation remain robust stabilisation pathways, especially for onion and spices, where moisture control and contamination risk strongly influence market value.

Circular valorisation of peels, pomace, and spice residues provides an important link between economic value and sustainability, but it must move beyond generic antioxidant claims toward specification-led pathways supported by stabilisation, contaminant screening, functional validation, and techno-economic assessment. Overall, value addition must be matched to commodity perishability and operational scale, from low-cost loss prevention at aggregation points to advanced ripening control, monitoring, and standardised biorefinery approaches at the industrial level. Near-term priorities include predictive shelf-life tools, packaging–produce matching rules, near-industrial validation of clean-label sanitation, and safe, standardisedvalorisation pipelines suited to Indian conditions.

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