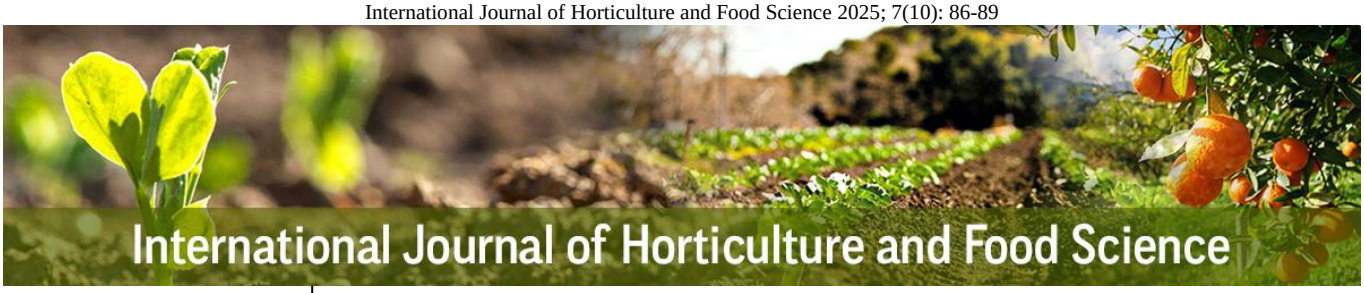

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Yuvraj Gopinath Kasal
Department of Farm Power and Machinery, Maharana Pratap Horticultural University, Karnal, Haryana, India

Satyapal Singh
Department of Vegetable Science, Maharana Pratap Horticultural University, Karnal, Haryana, India

Shahroon Khan
Department of Fruit Science, Maharana Pratap Horticultural University, Karnal, Haryana, India

Corresponding Author:
Yuvraj Gopinath Kasal
Department of Farm Power and Machinery, Maharana Pratap Horticultural University, Karnal, Haryana, India

Innovations in farm machinery for sustainable horticultural production: An Indian perspective

Yuvraj Gopinath Kasal, Satyapal Singh and Shahroon Khan

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Abstract
Horticulture is central to India's food security, nutrition and farm incomes. However, the sector is constrained by labour shortages, high post-harvest losses and limited access to appropriate machinery. Recent innovations — precision sensors and decision support, robotics and automation, electrified powertrains, protected-cultivation machinery and modular post-harvest units — can increase productivity, reduce resource use and lower losses. This review synthesizes technological advances applicable to Indian horticulture, quantifies current system metrics (production, losses, infrastructure), evaluates adoption drivers and barriers, and delineates priority R&D and policy actions to achieve sustainable mechanization. Key figures: horticultural production in 2022-23 ≈ 355.48 million tonnes; fruit production 2022-23 ≈ 110.21 million tonnes; India's cold-storage capacity ≈ 39.4 million MT in ~8,600 facilities; post-harvest losses remain high (variously estimated at ~15-30% for horticultural produce).

Keywords: Horticultural mechanization, precision agriculture, agricultural robotics, electrification, post-harvest loss, protected cultivation, India

Introduction
Horticulture in India is highly diverse and a major contributor to agricultural GDP and household nutrition. Final estimates for 2022-23 place total horticulture production at ~355.48 million tonnes, with fruit production alone ~110.21 million tonnes. Annual changes in area and production reflect both expansion and intensification of horticultural enterprises. The sector's value density, perishability and labor intensity make it a priority for targeted mechanization approaches that differ from broadacre solutions.
Sustainable mechanization must meet four concurrent goals: (1) increase labor productivity and reduce seasonal labor constraints; (2) reduce resource intensity (water, energy, agrochemicals); (3) minimize product damage and losses; and (4) be economically accessible for small and marginal farmers who predominate in India. This review examines technological trends and quantifies the current system status, highlighting opportunities for rapid, equitable impact.

Facts & figures — current infrastructure and losses (India)
Providing baseline metrics helps frame where machinery innovation can deliver the most benefit.

- **Total horticulture production (2022-23): ~355.48 million tonnes** (Final Estimates). Fruit production was ~110.21 million tonnes for 2022-23. These figures represent year-on-year increases and substantial national output.
- **Protected cultivation area:** Estimates vary by source — some surveys report ~11,000 **hectares**, while other compiled assessments indicate up to ~30,000 hectares under some forms of protected cultivation (polyhouse/greenhouse) depending on definitions and datasets. The divergence underscores differences in data collection (small tunnels vs commercial greenhouses) and rapid expansion in recent years.
- **Cold-storage capacity:** India has approximately 8,600 cold storage facilities with a combined capacity of ~39.4 million metric tonnes (as of recent analyses), but utilization, geographic distribution and suitability for fruits & vegetables remain uneven. Investment programs are underway to modernize and add solar and grid-hybrid cold rooms.

- **Post-harvest losses:** Estimates differ by methodology. FAO and policy briefs suggest that ~13-30% of food produced is lost from harvest to retail in developing contexts; India-specific estimates often place horticultural post-harvest losses in the range ~15-25%, with some aggregated studies noting up to ~30% for certain crops and value chains. Reducing these losses is a large lever for increasing food availability and farmer incomes.
- **Custom Hiring Centres (CHCs):** CHCs are a flagship mechanism to deliver mechanization access. District-level programs and national schemes have been funding CHCs; states and central schemes continue to expand CHCs with targets and achievements published by the Agriculture Mechanization portal. Recent state initiatives continue to add hundreds of CHCs annually to broaden access.

These baseline figures show both the scale of horticultural output and the infrastructure gaps — particularly in post-harvest cold chains and affordable mechanization access — that innovations must target.

Precision agriculture adapted to horticulture — concrete technologies and impacts

Sensor networks and micro-climate monitoring

Soil moisture sensors (capacitance, tensiometers) and canopy-based sensors allow micro-irrigation scheduling at bed or tree scale. Field deployments in orchards and polyhouses demonstrate water savings of 20-40% depending on irrigation baseline and control routines (case studies globally). Low-power telemetry (LPWAN, GSM gateways) supports real-time alerts and automatic irrigation triggers. Practical concerns for India: sensor calibration for local soils, durability in dusty environments, and affordable local repair networks.

Variable-Rate Application (VRA) & precision spraying

Spot-spraying and canopy-sensing sprayers use ultrasonic or LiDAR sensors to detect canopy gaps and foliage density to modulate nozzle output; trials in orchard crops reported pesticide savings of 20-50% in different cropping systems. This reduces chemical costs and off-target environmental exposure. A VRA approach for fertigation guided by soil & tissue sensors reduces nutrient leaching and optimizes fruit quality metrics (Brix, firmness).

Decision support systems (DSS) & local calibration

DSS platforms that integrate local weather, pest phenology models and sensor inputs are effective only when models are calibrated to local cultivars and management. India's heterogeneity (climate zones, cultivar mixes) necessitates region-specific models and offline functionality for low-connectivity areas.

Net impact: Precision systems deliver resource savings and can improve fruit quality and uniformity — critical for market access and export standards.

Robotics & automation — specific machinery, field performance and constraints

Robotic harvesters — state of play

- Robotic harvesters have matured for specific, controlled scenarios (e.g., greenhouse tomatoes, tunnel strawberries, some apple orchards). Leading prototypes combine RGB-D (depth) cameras, convolutional neural networks (CNNs) for fruit detection and soft grippers to reduce damage. Published research and commercial pilots show harvest rates are improving but still often below human pick rates and require crop/varietal standardization for efficiency.

Unmanned ground vehicles (UGVs) for weeding and maintenance

UGVs with mechanical weeding attachments or precision spot-spray systems reduce herbicide use and improve crop weed competition. Trials in high-value vegetable systems show potential for herbicide reductions ~50-90% for targeted systems. In India, low-cost UGV prototypes are being developed to suit small plot sizes and narrow rows; retrofit kits for tractor-mounted implements are a realistic near-term pathway.

Drones for scouting and application

Drones are widely used for high-resolution scouting (NDVI, multispectral imaging) and for low-volume targeted applications. Their benefits include speed of surveillance and access to steep terrain. Constraints include regulation (DGCA/NDRA frameworks), operator training and payload limits for heavy spray loads.

Human-robot collaboration and cobots

Cobots that enhance human pickers' ergonomics (positioning fruit, holding baskets) can raise throughput while deferring full automation investment — a promising transitional model for India's smallholder systems.

Key technical constraints: perception reliability in variable lighting, gripper adaptability across cultivars, energy autonomy for long field shifts, and cost parity vs labour. Research priorities include dataset creation of local fruit images and mechanically simple, low-cost soft grippers

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Electrification and renewable energy integration — scope and metrics

Electric micro-tractors and battery implements

Market reports and trials show increasing interest in electric tractors globally and in India. While diesel tractors dominate, electric alternatives are being developed for orchard and protected-cultivation use where lower noise and emissions are attractive. Market analyses forecast growth in electric tractor segments (global market CAGR projections in the mid-teens), and India's manufacturers are piloting electric models adapted to local farm tasks.

Solar + storage for irrigation and cold chains

Solar pumps with battery storage reduce reliance on grid power and diesel and can power micro-cold rooms for village pack-houses. India's cold-storage modernization programs include incentives for solarization; subsidies exist for cold-chain components under central schemes. With ~8,600 cold storage facilities and ongoing upgrades, solar + battery cold rooms can close significant gaps in horticultural cold chains.

Lifecycle and circularity concerns

Battery raw materials, recycling and end-of-life management must be integrated into electrification plans.

Lifecycle analyses comparing small electric tractors vs diesel for Indian tasks show promising energy and emissions benefits but depend on grid carbon intensity and battery lifecycle management.

Protected cultivation & mechanization in intensive systems

Machines tailored to greenhouse/polyhouse environments

Compact mobile platforms, trolley-mounted manipulators and modular pruning/harvesting attachments support intensive vegetable and floriculture systems. Automation of microclimate control (sensor-feedback loops controlling ventilation, shade nets and misting) improves uniformity in protected environments and reduces inputs.

High-density orchard mechanization

Mechanized platforms for pruning, thinning and harvesting in high-density plantings increase throughput. These include worker platforms (lifted) and mechanical pruners adapted to tree architecture.

Area under protected cultivation: Data shows rapid expansion but estimates vary (range cited above); this expansion increases the market for compact and modular mechanization solutions.

Post-harvest mechanization & cold-chain — practical units and cost metrics

Village/FPO level modular pack-houses

Modular units (grading, washing, conveyor sorters, small cold rooms) deployed at FPO levels reduce losses and increase value capture. Evidence from government schemes indicates high demand for such investments; subsidies for cold chain components are available (e.g., NHB cold chain schemes).

Grading & sorting with machine vision

Affordable vision systems now perform size, colour and defect sorting at modest throughputs suitable for small pack-houses. These systems reduce manual sorting time and improve market compliance for export and institutional buyers.

Quantified impact on losses and revenue

Field demonstrations indicate that access to basic pack-house and cold-storage can reduce perishability-related losses by ~10-20 percentage points and enable better market timing, improving farmgate prices. However, capital costs, power supply and maintenance are constraints.

Business models, financing and service delivery

Custom Hiring Centres (CHCs) & Equipment-as-a-Service

CHCs, supported by central/state programs, provide access to high-cost equipment. Government portals report district-wise targets and achievements; states continue to expand CHC networks, adding hundreds of centres annually to increase reach. CHCs' viability is improved by bundling operator training and maintenance services.

Farmer Producer Organizations (FPOs) and private service providers

FPOs aggregate demand for equipment and run local hire services. Private service providers (for spraying, harvesting) often succeed where markets for mechanization services are mature. Business model experiments (subscription, pay-per-use) show promise but require credit access and robust spare-parts networks.

Socio-economic, gender and labor transition aspects

Mechanization may displace some seasonal labor but can reduce drudgery (especially for women) and create new technical and service jobs. Gender-responsive design (lighter tools, adjustable handles) and inclusion of women in training and CHC operation increases equitable benefits. Reskilling programs and measured deployment can reduce adverse impacts.

Priority R&D and policy recommendations (detailed subpoints)

Technical R&D priorities

- **Perception datasets for Indian crops:** create annotated image datasets across cultivars, lighting and seasons to train robust AI models.
- **Soft-gripper standardization:** low-cost, repairable materials for gripping delicate fruits.
- **Retrofit autonomy kits:** add autonomous navigation modules to existing small tractors or power-tillers to reduce capital outlay.
- **Modular cold-chain components:** standardized, scalable pack-house modules that can be assembled and maintained locally.
- **Battery swap and second-life programs:** for electric implements to manage lifecycle and reduce upfront battery costs.

Extension, finance and regulation

- **Strengthen CHCs & FPO support:** scale CHCs focusing on horticulture-specific implements (platform harvesters, pack-house modules).
- **Subsidies tied to lifecycle performance:** prioritize machines demonstrating energy and water savings.
- **Standards and certification:** develop horticulture machine performance standards (damage rates, throughput) to protect growers and buyers.
- **Training and after-sales networks:** incentivize local manufacturing and spare-parts distribution to ensure uptime.

Conclusion

India's horticulture sector stands to gain substantially from thoughtfully designed farm machinery that prioritizes sustainability, affordability and maintainability. The scale of production (hundreds of millions of tonnes annually) and persistent post-harvest losses indicate large potential returns on investments in machinery, cold-chain, and service delivery. Coordinated R&D, policy support and business-model innovation (CHCs, FPOs, equipment leasing) will be pivotal to translating prototypes into widescale impact.

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