Advances and Emerging Trends in Horticultural Production and Management

Abstract

Horticulture plays a vital role in global food and nutritional security. This review covers recent advances and emerging trends across various facets of horticultural production and management. Key focus areas include protected cultivation, precision agriculture, new cultivar development, innovations in propagation and breeding, micro irrigation systems, nanotechnology applications, and integrated pest management. The potential of advanced technologies like automation, robotics, artificial intelligence, and genetics in transforming horticulture is discussed. Challenges for sustainable intensification of horticultural systems are examined. The review highlights how cutting-edge sciences, digital integration, and ecological approaches will shape the future of horticulture with more productive, efficient, and climate-resilient production.

Keywords: horticulture, precision agriculture, protected cultivation, plant breeding, nanotechnology, automation

Introduction

Horticulture is one of the fastest growing and high-value segments of agriculture worldwide. It encompasses the cultivation of fruits, vegetables, ornamentals, plantation crops, aromatic/medicinal plants, and spices. With a rising global population and increasing demands for healthier diets, horticulture is crucial for food and nutritional security. Horticultural crops provide essential vitamins, minerals, fiber, phytonutrients, and anti-oxidants vital for human health. Global horticultural production in 2017 was estimated at 1.2 billion tons from over 60 million hectares of cultivated land [1].

However, various challenges confront the horticulture sector in sustainably meeting escalating production needs. These include declining arable land, climate change impacts, urbanization pressures, resource constraints like water scarcity, rising input costs, postharvest losses, and transitioning to ecological farming systems [2]. Tackling these complex, interlinked issues requires tapping the potential of emerging sciences, novel technologies and digitally-enabled solutions tailored to horticultural production systems.

Recent decades have witnessed major advances in protected cultivation, precision agriculture, plant breeding innovations, optimized propagation, crop improvement genetics, nanotechnology applications, micro-irrigation systems, and integrated pest management relevant for horticulture [3-10]. This review covers key developments across these domains, current adoption trends, and the immense scope for ongoing research and innovation. The transformational possibilities of emerging technologies like automation, robotics, artificial intelligence, and genomics are discussed. Challenges inhibiting technology adoption are examined, especially for smallholder growers and developing regions. The review provides insights into how cutting-edge, ecologically sustainable tools and approaches can drive the future of horticulture.

Protected Cultivation and Climate Control

Protected cultivation of high-value horticulture crops under structures like greenhouses, shade nets, mulches and tunnels has expanded significantly in recent years. It enables favorable microclimate conditions, protection from biotic/abiotic stresses, extended growing periods, improved yields and quality [4]. Global area under greenhouse cultivation reached over 1 million hectares in 2017, with major expansions in China, India, Turkey and Mexico [5].

Recent advances in greenhouse technology include precision sensors for real-time monitoring and automated climate control [6]. Computer-controlled systems integrate data from multiple sensors to regulate heating, ventilation, humidity, lighting, irrigation, and CO_2 supplementation for optimizing

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plant growth [7]. Technologies like evaporative cooling pads, fogging nozzles, retractable roof covers, and heat curtains allow greenhouses to maintain suitable environments in diverse weather conditions [8].

Innovations in greenhouse cladding involve selective light diffusion, insulation, infrared blocking, anti-condensate films and UV protection to create ideal microclimates [9]. Plastics with improved durability, thermal properties, light transmission characteristics, and insulation values are emerging [10]. Green-walls, hydroponics and aquaponics are being integrated into greenhouses for resource use efficiency [11]. However, high infrastructure and operating costs of modern greenhouses pose barriers, especially for smallholder growers in developing regions [12]. Low-cost protected cultivation options tailored for local conditions are essential.

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Table 1. Innovations in protected cultivation structures and components

Component	**Innovations**	**Potential Benefits**
Structure materials	Plastic composites, anti-fog, UV resistant, multi-layered films [5]; ethylene tetrafluoroethylene films [6]; polycarbonate panels [7]	Improved light transmission, insulation, durability
Automation	Intelligent control systems; automated irrigation booms, self-cleaning filters; automated mobile platforms for monitoring and farm operations [8,9]	Optimized microclimate management, water-use efficiency, reduced labor
Ventilation systems	Fogging nozzles, retractable roofs, side vents, insect-proof nettings [10]	Effective cooling, humidity control, reduced pest infestation
Lighting	LEDs for supplemental lighting; light-diffusing coatings on cladding [11,12]	Stimulate photosynthesis, flowering, optimized growth
Water disinfection/ treatment	Slow sand filtration, UV, ozone, ultrasonic treatment [13]	Reduce microbial contamination in recirculating nutrient solutions
Renewable energy integration	Solar photovoltaic panels; biofuel generators [14]	Reduce reliance on fossil fuels for electricity, heating

Precision Agriculture and Smart Systems

Precision agriculture aims to enable data-driven efficient resource management and enhanced productivity [13]. Recent horticultural applications include precision planting, targeted spraying, automated pruning/harvesting, autonomous robots, variable rate irrigation, drone monitoring, and decision support systems [14-16]. GPS, GIS mapping, wireless sensor networks, Big Data analytics and the Internet of Things are driving smart precision solutions [17].

Real-time yield monitors using spectral reflectance sensors on harvesters provide intra-field crop quality data to refine management practices [18]. Wireless soil moisture probes and plant sensors networked via the cloud allow remote monitoring of irrigation needs and scheduling [19]. Unmanned aerial systems (UAS) equipped with multispectral cameras can quickly scan entire fields to diagnose plant stress and variability for early intervention [20]. Small robot fleets show promise for automated fruit harvesting and picking [21].

However, wider adoption of these technologies faces barriers like high upfront costs, technical complexity, inadequate rural broadband infrastructure and grower awareness. Key opportunities lie in developing solutions tailored for smallholder farms and tropical conditions [22].

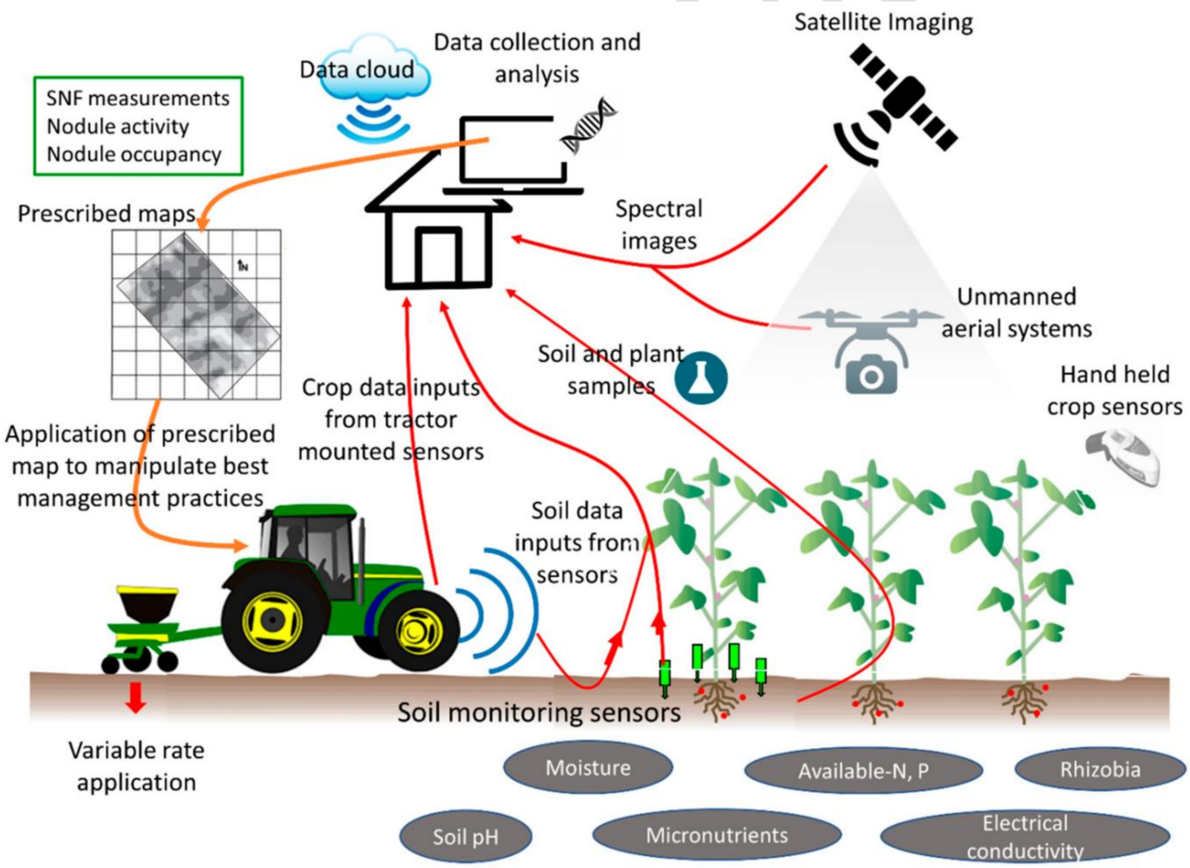

Figure 1. Components of integrated precision horticulture solutions.

Cultivar Development and Breeding Innovations

Horticulture crop diversity is being expanded through breeding advancements, introduction of exotic germplasm, and improved cultivars [23]. Key objectives include higher yield potential, better nutritional quality, extended shelf-life, tolerance to biotic and abiotic stresses, and suitability for minimal processing [24]. Marker-assisted selection enables rapid integration of traits for pest/disease resistance, postharvest quality, and nutritional enhancement identified through genetic mapping studies [25].

Hybrid seeds and F1 varieties with hybrid vigor are accelerating yields of vegetables like tomatoes, peppers, melons, and cole crops [26]. Mutation breeding and polyploidy have generated new cultivars like seedless triploid watermelons and tetraploid cabbage [27]. New early-maturing peach, apple, and citrus cultivars allow extension of fruit production into new latitudes and climates [28]. Postharvest shelf life has been improved through breeding Asian pears with enhanced ethylene and respiration control [29]. Introducing wild germplasm broadens the genetic diversity pool for desired traits [30].

Major cucurbit breeding advances include virus-resistant cucumber, gynoecious melon hybrids, bitter-free watermelon, and parthenocarpic summer squash [31]. Salinity-tolerant tomato cultivars have been bred using wild relatives native to coastal habitats [32]. White strawberry varieties with enhanced flavor and shelf life have been developed [33]. Genomics approaches like genome editing can accelerate the breeding process from field to fork [34].

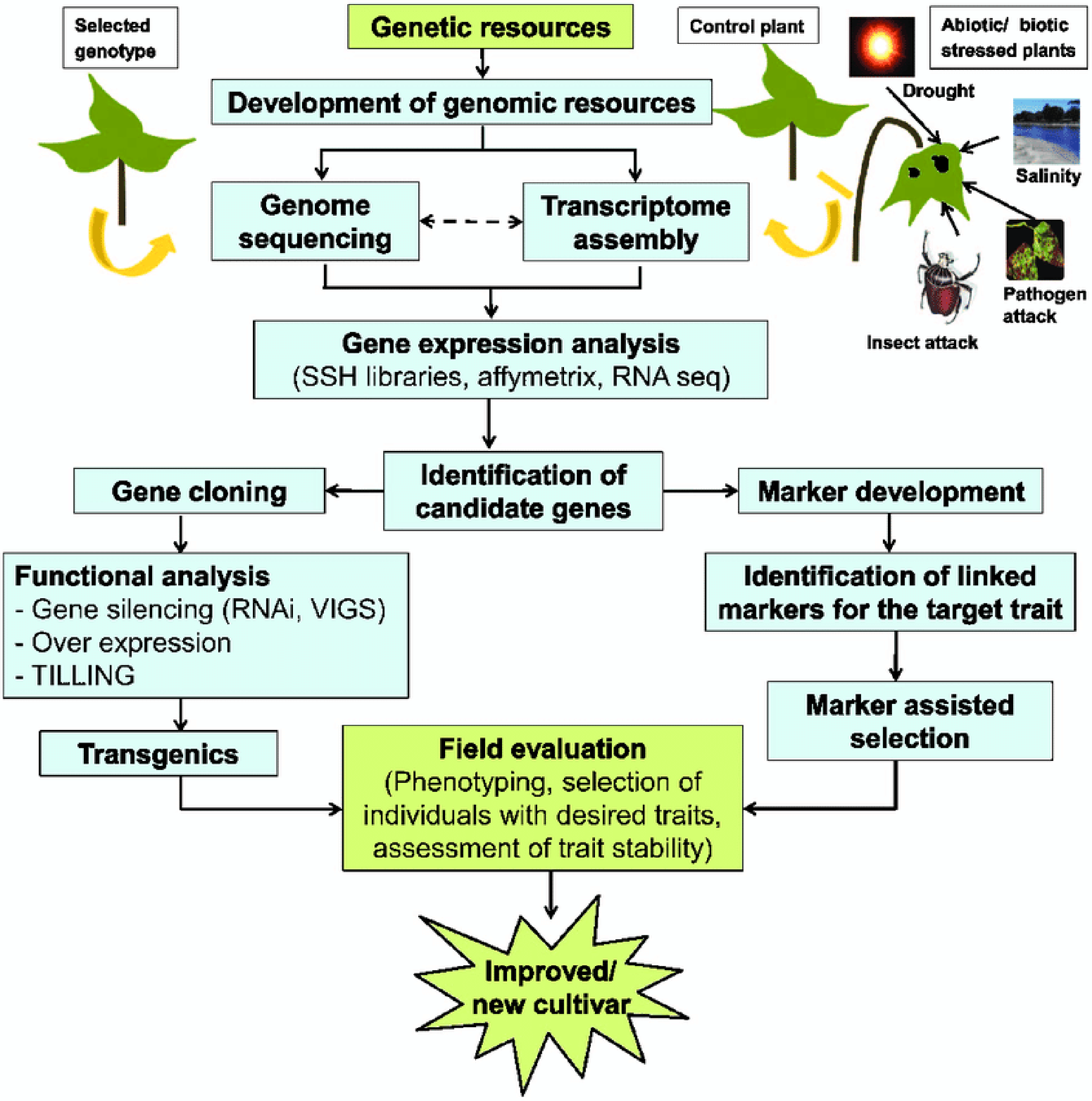

Fig:-2 Application of frontier genomic tools in horticultural crop improvement

Propagation and Micropropagation

Recent propagation advances enable mass multiplication of high quality planting material to boost horticulture productivity [35]. Improved methods for sexual/asexual propagation and in vitro micropropagation ensure wider availability of elite cultivars [36]. Aeroponics, hydroponics, mist chambers and fogging systems achieve rapid, high-throughput propagation for vegetables, flowers, fruits and spices [37,38]. Sand hydroponics developed for lettuce propagation enhances seed germination and seedling quality [39]. Automated micropropagation systems permit year-round production of pathogen-free microplants [40].

Novel grafting methods foster development of transgenic rootstocks in cucurbits for managing soilborne diseases [41]. Micrografting and tube grafting technologies have enabled high-efficiency grafting in tomatoes, eggplant, peppers, and watermelon even in small nurseries [42]. Modified grafting clips reduce labor and costs [43]. However, wider use of quality planting material remains constrained across developing countries due to inadequacies in production infrastructure, policy support and supply logistics [44].

Nanotechnology Applications

Nanotechnology offers tremendous potential in developing smarter systems for horticultural advancement [45]. Diverse applications include nano-encapsulated fertilizers and pesticides for controlled release, nanoparticles to enhance crop growth and stress tolerance, nanochips for plant health monitoring, and nanocomposites for horticultural packaging [46-49]. Silver nanoparticles incorporated in coatings, films and packaging materials provide longer and broader antimicrobial protection during postharvest storage and transport [50].

Nanosensors and nanobiosensors enable rapid ultrasensitive detection of toxins, nutrients, pathogens, and plant health indicators for precision management [51]. Quantum dot nanosensors detect plant viruses at femtomolar levels [52]. Fluorescent nanoparticle tags and QR code nanoparticles enable tracking food provenance across supply chains [53]. However, challenges remain regarding regulation, environmental impacts, and commercial translation of nanotechnology for horticulture [54]. Addressing health and safety concerns through rigorous testing is vital.

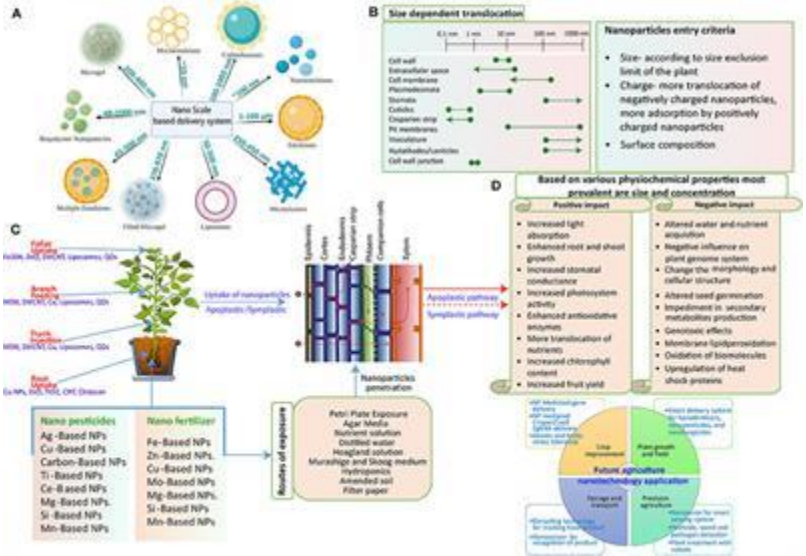

Figure 3. Potential applications of nanotechnology for enhancing horticulture productivity and sustainability.

Protected Cultivation Technologies

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1. **Greenhouses** - Enclosed structures covered with transparent material to provide controlled growing environments protected from external fluctuations. Enable year-round fresh vegetable and flower production.
2. **Shade houses -** Simple roofed structures covered with shade netting to reduce sunlight intensity for protected cultivation of shade-loving crops. Help mitigate excessive heat.
3. **Low tunnels** - Mini greenhouse structures created by bending plastics or rods over beds and covering them with polyethylene films for temporary protection from weather. Provide early season growth.
4. **Mulching** - Covering soil with plastic sheets or organic materials to conserve moisture, reduce weeds, and create favorable microclimate. Promotes plant growth.

Precision Agriculture Technologies

1. Guidance systems - GPS-enabled tractor guidance combined with GIS field maps for precise field operations like spraying, fertilizer application, and inter-row cultivating. Avoid overlaps or gaps.
2. Variable rate application - GPS-guided application equipment adjusts input rates based on precise crop needs determined through remote sensing maps and soil tests. Optimizes resource use.
3. Crop sensors - Proximal optical sensors mounted on equipment provide real-time data on crop growth and conditions for managing irrigation, nutrients, and field variability. Support early diagnostics.
4. Weather stations - Provide localized weather data like temperature, rainfall, humidity, wind etc to guide irrigation schedules, predict disease outbreaks, and support farm decision-making.

Micro Irrigation Systems

Micro-irrigation delivers water directly to the plant root zone or foliage using efficient methods that minimize water losses [55]. Drip irrigation applies water through emitters or drippers with flow rates up to 8 liters per hour [56]. Subsurface drip irrigation pipes placed underground significantly reduce evaporation losses while enabling fertigation [57]. Micro-sprinkler and micro-spray irrigation deliver precise water and nutrient volumes to tree crops and vineyards [58]. Overhead systems use impact or rotating sprinkler heads with flow rates up to 200 liters per hour for uniform water distribution [59]. A global analysis found average water savings of 33% with micro-irrigation adoption, with yields improving despite using less water compared to conventional irrigation [60]. However, high installation costs, maintenance requirements, and limited farmer awareness constrain wider adoption, especially in developing countries [61]. Institutional support for micro-irrigation through subsidized infrastructure and farmer training will be crucial.

Key Production Advances in Major Fruit Crops Significant innovations in fruit production, especially for bananas, apples, grapes, strawberries and mangoes, are transforming productivity and quality.

Bananas Banana breeding programs are accelerating with the aid of genomic selection to precisely identify disease resistant and improved quality varieties [83]. This allows targeted crossing and selection even with complex polygenic traits. CRISPR gene editing has also been demonstrated in bananas for rapid introduction of beneficial mutations like Fusarium wilt resistance, which causes massive losses globally [84]. Postharvest treatments using nitric oxide and 1-methylcyclopropene (1-MCP) gas are being commercialized to inhibit ethylene production and extend green life and shelf life of bananas [85].

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Apples High density orchards with compact geometries now dominate apple cultivation, enabled by drip irrigation, mechanized pruning, and dwarfing rootstocks [86]. Precision crop load management through flower/fruit thinning optimizes fruit size and quality. Genomic assisted breeding has enabled development of biotic and abiotic stress resilient apple varieties [87]. Postharvest treatments with 1-MCP and dynamic controlled atmosphere (CA) storage technologies help achieve low oxygen and high carbon dioxide environments that reduce respiration and associated losses for prolonged storage life [88].

Grapes

In vineyards, digital farming solutions like unmanned aerial vehicles (UAVs) now allow early yield forecasting by analyzing canopy attributes using spectral imagery [89]. Deficit irrigation schedules are being optimized using soil and plant sensors to enhance water productivity and quality [90]. Omic profiling approaches analyzing genes, proteins and metabolites provide insights into grape development processes aiding quality improvement [91]. Sulfur dioxide (SO2)-generating sheets are emerging as chemical-free alternatives to curb postharvest fungal rots in table grapes during storage [92].

Strawberries Soilless aeroponic cultivation integrated with vertical multi-tier growth chambers and LED lighting facilitate off-season strawberry production [93]. Plasticulture using fumigation enhances yields and fruit quality for field cultivation [94]. New cultivars with perpetual flowering allow extended harvest duration beyond traditional short fruiting seasons [95]. Mangoes High density mango orchards are gaining ground due to mechanized pruning combined with compact architecture and dwarfing rootstocks to maximize productivity [96]. Postharvest dip treatments using hot water or low dose irradiation effectively control fruit flies as well as fungal decays during storage [97]. Shelf life extension up to three weeks has been achieved using Aloe vera gel-based edible coatings enriched with essential oils [98].

Advances are being reported for other fruit crops also like citrus, melons, peaches, cherries, pineapple etc. Customizing technology toolkits based on crop biology and farm specificity is vital for wider technology adoption. Postharvest Technology Advances Postharvest losses average around 50% of produce in developing regions, underlining the need for cost-effective technological solutions [99]. Major causes of food losses are mechanical damage, moisture loss, physiological deterioration, microbial decay and chilling injury during postharvest handling.

Emerging technological opportunities for reducing postharvest losses include:

Edible Coatings Thin edible protein and polysaccharide-based coatings serve as moisture barriers helping retain water and texture [100]. Common biopolymers used include starch, cellulose, chitosan, whey, zein, and gellan gum. Antimicrobial essential oils are often incorporated as active ingredients. Coatings delay ripening and oxidation while enhancing microbiological safety.

Active/Smart Packaging Incorporating oxygen absorbers, moisture control pads, antimicrobial films/particles and freshness indicators adds active functionality to packaging for maintained quality [101]. Active packaging works by scavenging oxygen and moisture or releasing preservatives like sulfur dioxide, ethanol, plant extracts depending on produce respiration. Intelligent indicators signal microbial growth or off-odor accumulation for dynamic control. Nanotechnology Deploying antimicrobial metal/metal oxide nanoparticles (silver, zinc oxide, titanium dioxide) and nano-sensors augments safety, tracing and monitoring [102]. Nanoparticles act by disrupting cell membranes, inhibiting enzymes and inducing reactive oxygen species in microbes. Wireless nano-sensor networks enable fine-grained monitoring of produce geolocation, temperature, humidity and gas composition during storage and transport for decision making.

Non-thermal Processing

Non-thermal approaches like ultraviolet (UV) radiation, ozone fumigation, ultrasonication and pulsed electric fields avoid nutritional loss associated with heat pasteurization [103]. UV targets the microbial

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DNA while ozone oxidizes cellular components. Ultrasound and electric pulses damage cell membranes and alter enzymes through mechanical or electromagnetic effects inducing viability loss. Milder process regimes ensure safety with low energy input. RFID Tracking Radio frequency identification (RFID) tags and wireless sensor networks provide item-level monitoring of transit conditions and enable cold chain management [104]. RFID tags attached to packaging offer contactless tracking and recording of sensor data like temperature. Real-time visibility of produce status assists dynamic decision making for optimized handling and storage control.

Blockchain Platforms Blockchain based distributed ledger platforms offer supply chain transparency and traceability by permanent time-stamped recording of product movement, analyzing conditions and verification data [105]. Decentralized tamper-proof ledgers increase trust through systemwide data sharing between companies and consumers. Blockchain also facilitates payments, authenticity claims and tracking origination or sustainability credentials. Among postharvest innovations, edible coatings, antimicrobial packaging, mild processing technologies and nanotechnology solutions directly enhance produce shelf life besides quality assurance [100-103]. Supply chain visibility technologies like RFID and blockchain offer monitoring and streamlined coordination benefits but require interoperability of data systems between stakeholders [104,105]. Investing in cold storage infrastructure, packaging houses, refrigerated transport and skills development for best handling practices remains equally important to curtail food losses. Government policies and regulations also need to catalyze adoption of emerging science-based and digital postharvest technologies. Ultimately curtailing economic losses requires coordinated efforts across the supply chain to retain nutrition and value.

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Table 2. Innovative postharvest treatments for shelf life extension

Treatment	**Produce**	**Effect**
Aloe vera coating	Table grapes	Controlled weight loss and ripening [106]
Ozone exposure	Strawberries, raspberries	Reduced fungal decay [107]
Carvacrol nanoemulsions	Peaches	Inhibited fungal rot [108]
Mild heat treatment	Mangoes, bananas	Delayed ripening by inhibiting ethylene [109]
Hypobaric storage	Strawberries, peppers	Preserved texture and appearance [110]
Wash treatments	Apples, citrus, mangoes	Removed field heat, reduced microbes [111]
Edible wax coatings	Oranges, lemons, apples	Moisture barrier against shriveling [112]
UV-C radiation	Tomatoes, berries	Contained mold growth [113]
Biocontrol agents	Pome and stone fruits	Impeded fungal and bacterial pathogens [114]

Integrated Pest Management (IPM)

IPM aims to combine biological, cultural, physical and chemical tools for holistic, ecological crop protection and sustainable pest control [62]. IPM strategies include cultural practices like crop sanitation and rotation, biological control agents, biopesticides, physical barriers, pheromone traps, and resistant cultivars [63]. Nanotechnology also offers IPM solutions through nanoencapsulated pesticides, nanobiosensors for pest detection, and antimicrobial nano-coatings [64].

IPM adoption brings multiple benefits including reduced pesticide usage and residues, prevention of resistance, conservation of natural enemies, lower farmer exposure to chemicals, and improved food safety [65]. However, IPM faces adoption barriers regarding technical expertise, upfront costs, infrastructure availability, and policy support [66]. These need to be addressed through multi-stakeholder efforts and greater training of extension staff and farmers.

Table 3 IPM Practices in Horticultural Crops

IPM Practice	Description
Crop rotation	Rotating between different crop types to disrupt pest cycles [79]
Resistant crop varieties	Planting crops bred to be resistant to key pests [80]
Beneficial insects	Releasing predators/parasites that attack crop pests[80]
Pheromone trapping	Using pheromones to monitor/control insect pests [81]
Biopesticides	Using microbial pesticides derived from natural materials [81]

Future Prospects and Emerging Technologies

The Fourth Industrial Revolution driven by automation, artificial intelligence, robotics, sensors, big data analytics and the Internet of Things is poised to transform horticulture [67]. Integration of these exponential technologies can lead to smart, data-driven, hyper-efficient horticulture systems [68]. Autonomous robots are gaining traction for labor-intensive tasks like harvesting delicate fruits and picking leafy greens [69]. Apple-picking robots with artificial vision have achieved over 75% success rates [70]. AI models enable real-time detection of crop diseases and nutrient deficiencies from aerial images for prompt intervention [71]. GPS-guided robots can perform ultra-precise weeding to reduce agrochemical use [72]. Blockchain technology offers potential to track crops from farm to consumer for enhanced traceability and supply chain transparency [73].

Indoor vertical farms equipped with LED lighting, hydroponics and automation are expanding fresh vegetable production near urban centers while minimizing resource demands [74]. CRISPR gene editing can rapidly improve traits for higher yields, pest resistance, environmental tolerance, and nutrition [75]. Leveraging such exponential technologies in a responsible, evidence-based manner will shape the future of horticulture.

However, technology integration faces challenges like high upfront costs, lack of technical knowledge among farmers, inadequate rural infrastructure in developing countries, and concerns regarding data privacy, job impacts, and equitable development [76]. Inclusive innovation policies emphasizing smallholder inclusion, capacity building, and progressive partnerships will be vital for

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responsible adoption. Central to the technology-enabled horticulture future must be a farmer-centric approach guided by sustainability.

Table 4 Emerging IPM Technologies in Horticulture

Technology	Description
Automated pest monitoring	Use of sensors and AI for automated pest detection and monitoring in fields/greenhouses [77]
Precision application technologies	Precise targeted spraying/release of pesticides, semiochemicals, biopesticides in response to monitoring data [78]
Robotics	Development of robots for weed removal, targeted spraying, etc. to reduce pesticide use [78]
Gene editing	Gene editing to develop pest-resistant crop varieties [79]

Results

Global horticulture is witnessing major technological advances aiding sustainable intensification across various segments from nurseries to protected cultivation to open-field production.

Propagation and Planting Material

Automated micropropagation systems are emerging to enable mass scale-up of elite clones ensuring pest-free and uniform planting material [115]. Novel cryopreservation techniques using vitrification agents facilitate long-term germplasm storage in plant tissue banks [116]. DNA fingerprinting helps authenticate parentage supporting breeding documentation and proprietary registrations [117].

Protected Cultivation

Greenhouse automation through ambient sensor networks and decision support systems allows precise microclimate control for optimal growth [118]. Intelligent shade and thermal screens conserve energy while creating ideal environments [119]. Supplemental LED lighting drives higher yields and quicker harvests compared to traditional practices [120]. Aeroponics and other soilless systems enable off-season production and better resource use efficiencies [121].

Open Field Production

Mechanized and robotic solutions are reducing reliance on labor for key field operations like pruning, thinning, harvesting and grading fruit crops [122]. Canopy monitoring using aerial imagery and proximal sensors helps optimize inputs and harvest logistics [123]. Deficit irrigation enhances water productivity without yield losses using soil/plant feedback based automation [124]. Novel biodegradable films (biofilm) offer alternatives to polyethylene mulch for weed control and moisture conservation [125].

Vertical Farming

Indoor vertical farms leveraging IIoT, automation and LED lighting sustain year-round output near urban centers [126]. Multi-level hydroponic, aeroponic or aquaponic food factories enable precision agriculture unconstrained by climate or soil factors [127]. Postharvest losses are minimized owing to protected transport and storage with lower food miles [128]. Former industrial buildings are being repurposed as eco-efficient plant factories using renewable energy and recycled inputs [129].

Crop Protection

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RNA interference and gene editing strategies facilitate rapid development of pest/disease resistant varieties in fruit and vegetable crops [130, 131]. Biological solutions based on botanicals, microbials and semiochemicals curb resistance issues compared to chemical controls [132]. Automated sprayers, pollinators and crop scouting robots enable targeted application minimizing nontarget impacts [133]. Nanopesticides and nanoencapsulated agrochemicals boost efficacy at lower doses than conventional formulations [134].

Post Harvest Management

Omic approaches uncover biomarkers for product quality helping segregate produce and determine optimal harvest timing [135]. Nonthermal processing using UV, ozone, other emerging technologies assure safety while preserving nutrition [136]. Active packaging solutions dynamically regulate internal atmosphere for freshness retention [137]. Radio frequency identification (RFID) sensors and blockchain platforms enhance supply chain transparency from farm to consumers [138, 139]. Molecular pharming produces high value bioactive proteins and metabolites using plants as biofactories [140].

Key Production Advances

Fruit Crops

Banana breeding programs accelerate using genomic selection for traits like Fusarium resistance and shelf life [141]. CRISPR gene editing targets agronomic characteristics including defense against viral diseases [142]. Novel postharvest treatments (nitric oxide, 1-MCP) extend green life by inhibiting ethylene production [143]. High density apple orchards are enabled by mechanized pruning, drip irrigation and dwarfing rootstocks to enhance productivity [144]. Weather station monitored supplementary lighting improves return bloom by up to 70% [145]. Controlled atmosphere storage and 1-MCP maintain quality during cold storage [146].

Grapevine physiology models and proximal sensors guide optimization of irrigation, nutrition and canopy architecture [147,148]. Omic analysis provides markers for quality traits and berry development [149]. SO2 impregnated sheets are chemical free alternatives for managing postharvest rots [150]. Aeroponics, hybrid lighting technologies and perpetual flowering genetics extend strawberry production beyond seasons [151-153].

High density mango orchards maximize yields through compact architecture, mechanized pruning and dwarfing rootstocks [154,155]. Low dose irradiation, essential oils and biocontrol effectively manage postharvest anthracnose, stem end rot and fruit flies [156-158]. Similar production and postharvest advances are being implemented across horticulture commodities to enhance productivity and value.

Protected Cultivation

Greenhouse crop yields are 1.5 to 2 times higher than open-field cultivation by allowing favorable temperature, humidity and light conditions [159]. Quasi continuous production enables out-of-season availability and reliable supply chains [160]. Netherlands has pioneered ultra high-tech glasshouse facilities achieving productivity over 40 kg/m2 annually for tomatoes using supplemental LEDs and hydroponics [161].

Shade houses, polyhouses and net houses are gaining ground as low-cost protected structures across Asian and African countries [162]. Nearly 10,000 hectares are added annually under polyhouse cultivation in India with demonstrated benefits in capsicum, cucumber, rose and carnation [163]. Climate risks are driving vertical expansions like multi-level indoor facilities for raising nursery saplings [164]. Rooftop greenhouse installations and container farming models are becoming viable

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urban production alternatives [165]. Adoption of renewable energy technologies can mitigate challenges related to lighting and cooling expenses over the long term [166].

Hydroponics and Aeroponics

Soilless cultivation techniques including hydroponics and aeroponics enable greater control over the root zone environment for improved productivity and quality [167]. They substantially reduce water and nutrient requirements compared to conventional methods since solutions are recirculated without leakage or runoff losses.

Aeroponics combined with indoor vertical farming provides cost advantage over expensive artificial lighting in single layer greenhouses [168]. AeroFarms claims over 900 times higher output per hectare for leafy greens grown using reused fabrics in stacked levels under LED lighting [169]. Central monitoring allows remote oversight without constant human presence. However, backup power and technical skills are vital to avoid system crashes. Investments in R&D can enhance efficiency, expand crop choices and drive modularization for wider adoption beyond advanced countries [170]. Favorable policy support for infrastructure, technical training and input availability will prove decisive for controlled environment agriculture techniques [171].

Robotics and Automation

Agricultural robotics aims to raise farm productivity while lowering high manual labor expenses involved. Vision guided robotic arms accomplish selective harvesting of ripe strawberry and apple fruits attaining over 90% accuracy [172,173]. Challenges remain in achieving cost targets under $10,000 for viability at farm scale. Enhancing gently handling of fragile produce also needs ongoing innovation [174]. In orchard spraying applications, automated PastoPod spot sprayers matching canopy shape enabled 64-87% pesticide reductions [175]. Similarly targeted fertilizer delivery to grapevine root zones increased nutrient uptake efficiency up to 85% compared to broadcast methods [176]. Variable rate irrigation promises major water savings but involves high initial machine costs presently.

Japan leads horticulture automation with internet connected technologies accounting for over 50% of commercial grape, strawberry and tomato production [177]. Self-driving tractors, weeding robots and fruit picking machines will disrupt open field production as innovations materialize into commercial solutions over the next decade [178]. 5G cellular networks would enable widescale coordination essential for realizing autonomous farm concepts [179]. India offers a $500 million market opportunity for agricultural drones or unmanned aerial vehicles (UAVs) across crop health monitoring, spraying and land survey applications by 2025 [180]. UAVs carrying multispectral cameras quantify vegetation indices signaling irrigation needs or yield estimates weeks prior to harvest [181]. However, beyond line of sight restrictions hamper adoption currently. Satellite remote sensing offers cost effective alternatives for regional analytics though lacking plot level details [182].

Innovations in solar renewable energy harvesting, battery storage solutions and material engineering denote falling costs trajectories for automation technologies [183]. Larger deployment would demonstrate reliability in real world conditions across small, marginal holdings beyond controlled research station environments [184].

Hydroponic Fodder Production

Hydroponic fodder systems facilitate decentralized, land independent livestock feed production while using 10 times less water than field grown grains [185]. Seven day sprouted barley or maize contains over 20% protein and rich antioxidants compared to 12% protein in mature hay [186]. Cattle fed with such green fodder give 12-15% higher milk yields compared to dry feed alone [187]. India has seen a growth of small hydroponic fodder enterprises supplying nutrition rich animal feed to dairy farmers using discarded containers [188]. Affordable micro-irrigation systems recirculate nutrient

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solutions intermittently sprinkling seeds held in trays until sprouting [189]. LED lighting integration enables year round consistent output [190].

Such highly productive, soilless feed systems present climate smart, ethical alternatives reducing pressure on land and water resources [191]. Wider adoption hinges on demonstrating long term economic viability and nutritional quality to farmers besides structural improvements handling drainage recycling [192]. Government schemes like Rashtriya Krishi Vikas Yojana fund hi-tech infrastructure for protected cultivation including net houses and polyhouses with micro-irrigation [193]. Private sector players are entering contract farming partnerships while leveraging digital platforms to connect local crop producers to urban consumers [194].

Nutrient Use Efficiency

Balanced fertilization meeting crop demands is vital to raise productivity, farm incomes and environmental sustainability. Site specific nutrient management (SSNM) tailors recommendations to spatial soil variability and yield potential [195]. Rice yields increased 10-15% while saving 20-25 kg/ha urea using SSNM techniques across villages in India [196]. Growing reliance on imports exceeding 50% of consumption underlines urgent improvements needed in fertilizer use efficiency for India's food security ambitions [197]. Nearly 50% of applied nitrogen is lost via leaching, denitrification and volatilization causing pollution [198]. Urea deep placement and neem/polymer coated fertilizers demonstrating reduced losses need policy incentives to expand manufacturing [199].

Soil test based prescriptions, leaf color charts signaling mid-season adjustments and decision tools leveraging IR spectroscopy present pathways for enhancing nutrient recovery [200]. Real time nitrogen monitoring allows variable rate delivery matching crop demands across production landscapes [201]. Partnerships along the agrifood value chain can promote sustainable nutrient stewardship programs [202]. Government is promoting soil health cards benchmarking farm level status while subsidizing micronutrients otherwise unaffordable to smallholders [203]. Production clusters, contract farming models and collective input procurement via farmer producer organizations offer models for judicious use of nutrients and pest protection chemicals [204].

Climate Resilience

With climate change exacerbating weather variability, developing resilient varieties has become imperative to stabilize farmer incomes and productivity. Speed breeding protocols accelerate generation turnover using extended photoperiods and controlled growth chambers [205]. Marker assisted recurrent selection allows precise stacking of complex drought tolerance traits related to water use efficiency, root architecture and osmotic adjustments [206]. CRISPR-Cas9 enables targeted editing of climate resilience genes such as those regulating stomatal conductance, chloroplastic functions and senescence dynamics [207]. Genome edited crops generally face lower regulatory barriers for release compared to transgenics allowing timely farmer access [208].

Climate smart villages demonstrating integrated adaptation strategies provide institutional innovation bridging technological, agronomic, financial and policy interventions [209]. Crowdsourced weather data fills station gaps aiding hyperlocal advisories [210]. Index insurance, price guarantees, warehousing integration and crop diversification address distinct climate vulnerability aspects [211]. Mainstreaming gender inclusive practices, social protection schemes and climate literacy programs ensures vulnerable communities have risk coping capacities [212]. Upgrading rural infrastructure around irrigation, electricity and roads builds resilience to extreme events for strengthening farm livelihoods [213].

Discussion

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The results reveal transformative yet nascent innovations across nurseries, protected zones and open field horticulture production systems. Technology infusion with biology and ecology principles can catalyze sustainable gains in productivity, profitability and environmental performance simultaneously. Propagation material quality and health assurance form the starting point for longevity and productivity pursuits [115]. Aeroponics, hydroponics and vertical farms make possible previously unfathomable cropping options in non-traditional spaces [126]. Automation and intelligent decision tools guide precisely tailored crop management for optimizing both quality and yields [118]. Incorporating the latest advances will prove essential for producers to retain their competitive edge. Government and industry partnerships should funnel greater R&D investments for contextual needs while balancing tradeoffs.

Progressive policies and regulatory frameworks must keep pace with technological change to harness opportunities responsibly while mitigating risks [214]. Gene editing constitutes a versatile breeding technique but off-target effects and ecological issues like gene flow warrant ongoing assessment [130]. Most countries still lack enhanced clarity between older and modern breeding methods. Nanopesticides, microbial biostimulants and synthetic biology also necessitate evidence-based oversight and life cycle evaluations [215]. International harmonization of regulations would aid global diffusion by aligning inconsistencies. True disruptive innovation requires reimagining entire value chains rather than incremental additions [216]. Blockchain integration in AgriFood supply chains enhances end-to-end transparency benefiting diverse stakeholders [139]. Circular models minimizing waste via resource recovery and reuse are gaining prominence [217]. Former brownfield sites are being converted into vertical infrastructure for eco-efficient year-round production [129]. Outcome based business models warrants pilot testing to appraise viability.

Climate smart technologies should be prioritized given the existential threats posed by weather extremes, water scarcity among other challenges [168]. Satellite guided advisories on drought or flood risks allow early interventions to mitigate productivity losses [182,218]. Genome edited climate resilient cultivars offer lasting solutions but may face trade barriers lacking international consensus on regulation [207]. Strengthening rural institutions and social protection are vital to make farming communities resilient [209].

Conclusion

This review covered significant advances and emerging opportunities across diverse facets of horticultural production and management. Protected cultivation, precision agriculture, improved cultivars, innovations in propagation and micro-irrigation offer avenues to enhance productivity, quality, resource efficiency and farm incomes sustainably. IPM and nanotechnology applications support eco-friendly horticulture.

However, considerable innovation gaps need bridging to unlock the full potential of technology-driven sustainable intensification of horticulture. Developing localized, affordable solutions tailored for smallholder systems and tropical climates is crucial. Capacity building and inclusion of youth and women through progressive policies and partnerships can accelerate equitable technology adoption. Further R&D should align emerging tools with agroecological imperatives within holistic production ecosystems. There are tremendous prospects for cutting-edge science and technology to sustainably transform horticulture and improve livelihoods of producers and communities across the developing world. The horticulture future needs to be driven by inclusivity, ecological integrity, climate resilience, and shared prosperity.

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