International Journal of Plant & Soil Science

Volume 38, Issue 5, Page 347-365, 2026; Article no.IJPSS.158317
ISSN: 2320-7035

Advances of Soilless Cultivation on Flower Crops: A Review

Ajuli Borgoyary [a*], Subhankar Saha [b], Kankana Deka [a], Nilay Borah [c], Pradip Chandra Dey [d] and Utpal Kotoky [a]

[a] *Department of Horticulture, Assam Agriculture University, Jorhat, India.*
[b] *Department of Hoticulture, Sharat Chandra Singha College of Agriculture, Dhuri, India.*
[c] *Department of Soil Science, Assam Agriculture University, Jorhat, India.*
[d] *Department of Plant, Physiology, Assam Agriculture University, Jorhat, India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2026/v38i56086

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here:
https://pr.sdiarticle5.com/review-history/158317

Review Article

Received: 28/02/2026
Published: 21/05/2026

Abstract

Soilless cultivation has emerged as a transformative approach in modern floriculture, offering precise control over the root environment and overcoming many of the limitations historically associated with soil-based production. This review examines principal advances in soilless cultivation technologies as applied to flower crops, encompassing hydroponic, aeroponic, and substrate-based systems. Developments in growing media are evaluated, including the adoption of coconut coir, perlite, rockwool, and emerging biochar-based substrates as alternatives to conventional peat. The literature underlying this review was identified through systematic searches of the following academic databases: Web of Science (Clarivate Analytics), Scopus, Google Scholar, PubMed/MEDLINE, CAB Abstracts (Centre for Agriculture and Biosciences International), AGRIS (Food and Agriculture Organization of the United Nations), the Horticulture Research Information Service (HRIS), FSTA – Food Science and Technology Abstracts, and AGRICOLA (National Agricultural

---

**Corresponding author: E-mail: ajuli.borgoyary.amj24@aau.ac.in;*

***Cite as:** Borgoyary, A., Saha, S., Deka, K., Borah, N., Dey, P. C., & Kotoky, U. (2026). Advances of Soilless Cultivation on Flower Crops: A Review. International Journal of Plant & Soil Science, 38(5), 347–365. https://doi.org/10.9734/ijpss/2026/v38i56086*

Library of the United States Department of Agriculture). The management of nutrient solutions—covering pH, electrical conductivity, and macro- and micro-element ratios—is discussed in relation to optimising floral quality and yield. Advances in light-emitting diode (LED) technology are reviewed with respect to their capacity to manipulate flowering time, stem elongation, and secondary metabolite accumulation in ornamental species. Water use efficiency and the environmental sustainability of recirculating versus open soilless systems are critically assessed. Applications to commercially important species—including rose (*Rosa* spp.), chrysanthemum (*Chrysanthemum* × *morifolium*), gerbera (*Gerbera jamesonii*), *Phalaenopsis* orchids, and *Pelargonium* spp.—are examined in detail. Post-harvest quality and vase life are considered as functions of pre-harvest nutrition and substrate composition. The review concludes by identifying key research gaps and future directions, with particular emphasis on precision fertigation, digital sensing technologies, and the integration of soilless systems into sustainable circular production models.

Keywords: Hydroponics; floriculture; nutrient solution; growing substrate; LED lighting; nutrient film technique; water use efficiency; recirculating systems; cut flower quality; ornamental horticulture.

1. Introduction

The soilless culture system is a promising, intensive, and sustainable approach with various advantages for plant production. The increased worldwide production of crops in controlled environmental systems has been further accelerated by the increased interest in growing small/soft fruit crops, greens, herbs, and cannabis in soilless container systems. In addition, they are used to increase metabolites in medicinal and aromatic plants and to introduce new crops (Gruda, 2022). Continuous cultivation of crops in soil throughout many decades has resulted in poor soil fertility, increase of salinity or infestations by pathogenic organisms. This situation has led to poor yield and quality of crops. Furthermore, some soils in the world are not suitable for plant growth for being poorly textured or shallow, degraded due to erosion or too close to metropolitan areas. Whenever soil conditions are unfavourable, soilless culture can be a solution (Gebreegziher, 2023).

1.1 Global Significance of Flower Crop Production

The global floriculture industry represents one of the most economically dynamic sectors within horticulture, characterised by steady growth in both production value and international trade. Cut flowers, potted ornamental plants, and flowering bedding species are cultivated across a broad range of climatic zones—from the temperate, climate-controlled greenhouse industries of the Netherlands, Germany, and Belgium to the open-field production regions of Colombia, Kenya, Ecuador, and Ethiopia. The Netherlands has historically accounted for approximately half of the global cut flower trade by auction value, functioning as both the principal production hub and the dominant re-export centre, whilst emerging producing nations in East Africa and South America have progressively captured market share on the strength of lower labour costs and favourable natural growing conditions (Savvas & Gruda, 2018). The ornamental plant sector, encompassing all flower crops, supports millions of livelihoods globally and generates annual trade values that are consistently measured in the tens of billions of United States dollars.

Despite its considerable economic importance, conventional soil-based floriculture confronts several well-documented and interconnected challenges. The progressive deterioration of soil structure through intensive monoculture is among the most persistent concerns, as prolonged cultivation of the same species in the same soil leads to the build-up of phytotoxic compounds, accumulation of soil-borne pathogens such as *Fusarium* and *Pythium* spp., and the gradual depletion of mineralogical diversity. The difficulty of precisely controlling nutrient availability in heterogeneous field soils, and the environmental burden associated with excessive fertiliser application and the subsequent leaching of nitrates and phosphates into surface and groundwater, further compound the sustainability challenges facing the sector. Against this backdrop, growing societal and regulatory pressure to reduce pesticide and synthetic fertiliser inputs, alongside increasing water scarcity in many flower-growing regions, has substantially accelerated the adoption of soilless cultivation technologies in commercial floriculture worldwide.

1.2 Soilless Cultivation: Definition and Rationale

Soilless culture encompasses any system by which plants are grown without the use of natural soil as the primary rooting medium. The root system may be supported by an inert or semi-inert substrate, suspended directly in nutrient solution, or periodically exposed to fine aerosol mists, depending on the specific system employed. The defining characteristic of all soilless methods is that plant nutrition is supplied entirely through carefully formulated aqueous nutrient solutions, enabling the grower to exert precise control over the composition, concentration, and timing of nutrient delivery (Sambo et al., 2019). This capacity for fine-grained environmental control represents one of the most compelling reasons for the adoption of soilless methods in floriculture, where uniformity of quality, predictability of production schedules, and freedom from soil-borne disease are not merely desirable but commercially imperative.

The earliest scientific investigations into soilless plant culture date to the work of nineteenth-century plant physiologists, most notably Knop and Sachs, and commercial adoption accelerated markedly from the mid-twentieth century. By the 1980s, recirculating hydroponic systems—particularly nutrient film technique (NFT) and rockwool-based drip systems—had become widespread in European greenhouse horticulture. The application of soilless technologies to flower crops specifically, however, developed somewhat later than their application to vegetable crops, partly owing to the more complex requirements of ornamental species with regard to flowering time, plant architecture, floral pigmentation, and post-harvest durability. The optimisation of soilless systems for the particular physiological needs of ornamental plants has been an active area of applied research over the past two decades (Savvas & Gruda, 2018; Sambo et al., 2019).

1.3 The Case for Soilless Floriculture

The floriculture industry presents a particularly strong case for soilless production for several convergent reasons. First, the high commercial value per unit area characteristic of flower crops justifies the capital investment associated with soilless infrastructure, including the installation of irrigation equipment, substrate systems, and automated control technology. Second, the marked sensitivity of many ornamental species to soil-borne pathogens—roses are highly susceptible to *Fusarium* crown rot; chrysanthemums suffer from *Agrobacterium*-mediated crown gall; gerberas are prone to *Phytophthora* root rot—creates a strong operational incentive to avoid soil as the growing medium entirely. Third, the ornamental value of flower crops depends substantially on attributes such as stem length, flower diameter, colour saturation, petal freshness, and vase life, all of which are directly influenced by the pre-harvest nutritional environment and can be finely tuned through precise soilless management.

The water requirements of floriculture are also considerable. In cut flower production facilities, irrigation constitutes one of the largest variable operational costs, and water use efficiency is therefore simultaneously an economic and an environmental imperative. Recirculating soilless systems offer substantial water savings relative to soil-based irrigation, with documented efficiencies significantly exceeding those achievable through optimised soil-based irrigation management in comparable production settings (Savvas & Gruda, 2018). In an era of increasing hydrological stress in many of the world's principal flower-growing regions, this efficiency advantage is likely to become progressively more decisive.

1.4 Scope and Objectives

This review aims to provide a comprehensive and critical synthesis of advances in soilless cultivation technologies as applied specifically to flower crops. It addresses the development and characterisation of growing substrates, the management of nutrient solutions, the role of artificial and supplemental lighting, irrigation and water management, and post-harvest quality in the context of soillessly produced ornamentals. Specific attention is given to major commercial species including rose, chrysanthemum, gerbera, orchid, and pelargonium. The review further examines sustainability dimensions and identifies research gaps and priorities for future investigation. It is intended as a reference for researchers, practitioners, and advanced students in ornamental horticulture and controlled environment agriculture.

2. Methods for Literature Selection

2.1 Databases and Search Strategy

The literature underlying this review was identified through systematic searches of the following academic databases: Web of Science (Clarivate Analytics), Scopus, Google Scholar, PubMed/MEDLINE, CAB Abstracts (Centre for Agriculture and Biosciences International), AGRIS (Food and Agriculture Organization of the

United Nations), the Horticulture Research Information Service (HRIS), FSTA – Food Science and Technology Abstracts, and AGRICOLA (National Agricultural Library of the United States Department of Agriculture). These databases were selected as the most comprehensive sources for peer-reviewed literature in the fields of horticulture, agronomy, plant science, and agricultural engineering, and together they provide broad and complementary coverage of research published across international outlets.

The primary search strings employed included combinations of the following terms: ("soilless culture" OR "hydroponic*" OR "aeroponic*" OR "substrate culture") AND ("flower*" OR "cut flower*" OR "ornamental*" OR "floriculture"); ("nutrient solution" OR "NFT" OR "deep water culture" OR "rockwool" OR "coconut coir" OR "perlite") AND ("rose" OR "chrysanthemum" OR "gerbera" OR "orchid" OR "pelargonium"); and ("LED lighting" OR "supplemental light*" OR "growing media") AND ("ornamental" OR "pot plant*" OR "floriculture"). The primary date range was set at January 2006 to December 2024, ensuring currency and relevance to contemporary practice, whilst classic foundational studies published before 2006 were included where their contribution to the field warranted supplementary citation.

2.2 Inclusion and Exclusion Criteria

Studies were included if they: (i) were published in peer-reviewed academic journals; (ii) were written in English, or carried English-language abstracts sufficient to assess relevance; (iii) directly addressed soilless cultivation, hydroponic, aeroponic, or substrate culture techniques applied to ornamental or flower crops, or reported on closely allied topics—such as nutrient management, growing media properties, LED lighting physiology, or water use efficiency—with clear applicability to floriculture; (iv) were published within the defined date range, or were acknowledged classic references with foundational status; and (v) employed sound experimental or analytical methodology. Exclusion criteria were applied rigorously and encompassed conference proceedings, book chapters, grey literature, patent documents, trade magazine articles, theses or dissertations, and non-peer-reviewed institutional reports. Every retained journal reference was required to carry a verifiable DOI.

2.3 Screening Workflow, Deduplication, and Study Selection

Following initial retrieval, titles and abstracts were screened independently against the inclusion criteria. Duplicate records arising from overlapping database coverage were identified and removed before full-text assessment. Studies that passed abstract screening were retrieved in full and subjected to detailed evaluation. Particular weight was given to methodological rigour—including replication adequacy, statistical reporting quality, and quantitative data reliability—and to novelty with respect to floriculture-specific applications. Studies of high citation frequency within the field, exceptional methodological quality, or unique and direct focus on flower crop soilless production were prioritised for detailed discussion within the review body.

2.4 Review Approach and Rationale

This article adopts a narrative rather than systematic review methodology. This choice reflects the heterogeneous nature of the relevant literature, which encompasses diverse crops, varied soilless system configurations, different climatic contexts, and a wide range of outcome measures, making formal meta-analysis or systematic quantitative synthesis impracticable without significant loss of contextual nuance. The narrative approach enables a more integrative treatment of evidence across interconnected topics, facilitating thematic synthesis and the identification of patterns and research gaps that a more reductionist systematic approach might obscure. This is consistent with established guidance on narrative review methodology, as articulated by Green et al. (2006), who recommend narrative approaches specifically for synthesising complex and heterogeneous fields in which the primary goal is conceptual integration rather than statistical aggregation.

3. Overview of Soilless Cultivation Systems for Flower Crops

3.1 Hydroponic Systems

Hydroponic systems deliver mineral nutrients directly to plant roots through aqueous solutions, either continuously or intermittently, without the involvement of a solid rooting medium as the primary nutritional source. The major variants—nutrient film technique (NFT), deep water culture (DWC), drip irrigation applied to inert substrate, and ebb-and-flow (flood-and-drain) systems—possess distinct hydraulic and operational characteristics that determine their suitability for particular flower crops and production contexts. In NFT, a thin, continuous film of recirculated nutrient solution passes over the roots in shallow channels or gutters, supplying nutrition whilst maintaining high root-zone oxygen concentrations through exposure to the surrounding air. This system was one of the earliest commercially adopted hydroponic configurations and remains relevant in rose and chrysanthemum cut flower production, particularly in systems designed for high-turnover scheduling (Savvas & Gruda, 2018).

Drip-to-waste and recirculating drip irrigation systems applied to mineral or organic substrates—most commonly rockwool slabs, coir bags, or perlite troughs—constitute the dominant approach in modern large-scale soilless floriculture. Nutrient solution is delivered at the base of each plant through individually placed emitters, and the drainage fraction either is collected and recirculated or is discarded, depending on system design. The choice between open drain-to-waste and closed recirculating configurations has fundamental implications for both crop management complexity and environmental impact. In open systems, drainage carrying residual nutrients is discharged to waste streams, contributing to potential eutrophication of receiving water bodies. Closed systems recapture and reuse this drainage, reducing both fertiliser inputs and environmental emissions, but require more sophisticated management to prevent the progressive accumulation of sodium and other non-plant-available ions, and to control the proliferation of waterborne pathogens within the recirculated solution (Savvas & Gruda, 2018; Sambo et al., 2019).

3.2 Aeroponic Systems

Aeroponics suspends plant roots in air and delivers nutrition through high-frequency, fine-droplet misting of nutrient solution directly onto the root surface. This approach achieves maximum root oxygenation and can enhance nutrient uptake kinetics relative to conventional hydroponic methods, making it particularly well-suited to crops where root proliferation and rapid nutrient absorption are critical (Lakhiar et al., 2018). In their comprehensive review of aeroponic technologies, Lakhiar et al. (2018) documented the substantially higher water use efficiency achievable through fine-mist aeroponic delivery compared with continuous-flow hydroponics, noting that water savings of up to 70% relative to conventional soil irrigation have been reported in some aeroponic studies. The technology's compatibility with vertical growing configurations, in which multi-tiered root-chamber assemblies maximise production per unit of floor area, makes aeroponics particularly relevant to urban and indoor floriculture proposals.

For the majority of commercial cut flower producers, aeroponic systems remain aspirational rather than routine, primarily because the precision-engineered nozzles required for fine misting are susceptible to blockage by mineral deposits and organic matter, and maintaining the required solution pressure and misting frequency demands reliable engineering infrastructure. Nevertheless, aeroponic techniques have demonstrated specific promise in the vegetative propagation of flower crops, where the combination of high root-zone oxygenation, pathogen-free mist, and rapid root initiation reduces propagation cycle times and improves the uniformity of rooted cuttings—attributes of direct commercial value to rose and chrysanthemum producers who rely on large volumes of uniform propagative material.

3.3 Substrate-Based Systems

Substrate-based soilless systems, in which an inert or semi-inert medium replaces soil as the physical support for the root system and the principal medium through which nutrient solution is distributed, represent the most commercially widespread approach in floriculture globally. The substrate serves to anchor the plant, retain appropriate proportions of moisture and air within the root zone, and facilitate the even distribution of irrigation water. Unlike in solution culture systems, the substrate introduces additional variables—including water retention capacity, air-filled porosity, cation exchange capacity, and pH buffering strength—that must be characterised and actively managed to ensure reliable crop performance (Gruda, 2019).

Rockwool (mineral wool), produced by spinning molten basalt rock or furnace slag into fine amorphous fibres, was for several decades the substrate of choice in European commercial greenhouse rose and chrysanthemum production, prized for its chemically inert nature and consistently reproducible physical properties. Total porosity in standard horticultural rockwool slabs typically exceeds 95%, and the balance between water retention and aeration can be adjusted during manufacture through fibre orientation and density. However, concerns about the environmental impact of spent rockwool disposal, given its non-biodegradable composition and the tightening of mineral wool landfilling regulations across European Union member states, have driven intensive evaluation of alternative substrates in both research and commercial settings (Gruda, 2019). The comparative merits of inorganic, organic, and novel substrates for soilless floriculture are discussed at length in Section 4. Deep-flow technique (DFT) and raft systems—in which plants are supported on buoyant boards floating on large volumes of aerated nutrient solution—have attracted limited application in floriculture relative to their widespread use in leafy vegetable production, though some research has explored their use for potted herbaceous ornamentals such as gerbera and chrysanthemum, where the buffering effect of a large solution volume on pH and EC fluctuations may be advantageous in small-scale production contexts (Savvas & Gruda, 2018).

4. Growing Substrates for Flower Crops in Soilless Systems

4.1 Conventional Inorganic Substrates

Mineral substrates have dominated commercial soilless floriculture since the 1970s. Rockwool remains widely used in rose and chrysanthemum production across northern Europe, valued for its chemically inert nature and tunable physical properties. Perlite, a thermally expanded volcanic glass, is another significant inorganic option—particularly in Mediterranean and Middle Eastern production systems—where its high drainage capacity and low water retention help manage osmotic stress risks in warm climates and where regionally abundant raw materials reduce input costs. Scoria, pumice, and natural zeolites have also been evaluated as substrate components for ornamental crops, though their use remains largely regional and is more common in developing production areas than in technologically advanced greenhouse systems (Gruda, 2019).

Notwithstanding their production benefits, conventional inorganic substrates carry important end-of-use liabilities. Spent rockwool slab disposal generates substantial volumes of non-compostable waste, and regulations on mineral wool landfilling have tightened progressively in several European countries. Perlite, whilst theoretically reusable after steam sterilisation, is susceptible to physical breakdown during repeated crop cycles, progressively reducing air-filled porosity and compromising its drainage and aeration performance. These constraints have reinforced the impetus—from both commercial and environmental directions—towards organic and renewable substrate alternatives.

4.2 Organic and Renewable Substrates

Sphagnum peat has historically dominated the composition of commercial growing media in floriculture, valued for its stable physical structure, high water retention capacity, and naturally acidic pH that suits many ornamental species. The increasingly regulated status of peat extraction in Europe, owing to the climate significance of peat deposits as long-term carbon stores and the ecological importance of mire habitats, has greatly accelerated the search for sustainable peat substitutes (Gruda, 2019). Coconut coir—a lignocellulosic by-product of the coconut processing industry, available in fibre, chip, and fine dust fractions—has emerged as the most commercially significant alternative. Abad et al. (2002) characterised the physico-chemical properties of several commercial coir dust products, identifying wide variation in particle size distribution, electrical conductivity, and cation exchange capacity depending on geographic origin and post-processing treatment. Their study found that, following appropriate buffering to remove excess sodium and potassium—an essential pre-treatment for most raw coir products—performance was broadly comparable to peat for containerised ornamental production, whilst also offering the distinct advantage of biodegradability at the end of the crop cycle.

Composted bark, wood fibre, and lignocellulosic by-products from the paper and forestry industries have been extensively evaluated as growing media components for floriculture, and whilst they can partially substitute for peat, their propensity for nitrogen immobilisation during the early stages of microbial decomposition requires careful adjustment of the fertiliser programme when they constitute a large substrate fraction (Gruda, 2019). Green compost and composted municipal solid waste have attracted interest for their organic matter content and potential to contribute beneficial microorganisms to the root environment, but variability in nutrient content, the possible presence of heavy metals or phytotoxic volatiles, and regulatory restrictions on the use of waste-derived materials in ornamental production have collectively constrained their commercial uptake.

4.3 Biochar and Novel Substrates

Biochar—the solid carbonaceous product of biomass pyrolysis—has attracted considerable research attention as a component of soilless growing media, primarily because of its capacity to improve substrate porosity, increase cation exchange capacity through surface charge chemistry, and modify the microbial community of the root zone in ways that may benefit plant health. The foundational ecological work of Glaser et al. (2002) on the ameliorative effects of wood charcoal in tropical agricultural soils—documenting consistent improvements in water retention, cation exchange, and nutrient availability—provided an important mechanistic basis for exploring biochar application in intensively managed soilless horticultural substrates.

In a floriculture-specific context, Conversa et al. (2015) demonstrated that incorporating biochar into the growing medium significantly influenced the growth and flowering of *Pelargonium zonale*. Their experiment showed that moderate biochar rates, particularly when combined with mycorrhizal fungal inoculation, promoted root colonisation, increased the number of flowering heads, and improved overall plant vigour. These benefits were sensitive to fertiliser rate, however, suggesting that biochar's effects are mediated partly through alterations in nutrient retention and availability that must be accounted for when designing the overall nutritional programme. Tian et al. (2012) investigated the potential of green waste–derived biochar as a peat substitute in growing media for the ornamental foliage plant *Calathea rotundifolia*, finding that at low substitution rates biochar maintained acceptable substrate physical properties and supported normal plant growth, but that higher rates progressively suppressed growth, consistent with observations of potential phytotoxicity in some biochar products—a finding that underlines the importance of careful product characterisation and rate optimisation before large-scale adoption in commercial floriculture.

4.4 Substrate Chemistry and pH Management

Irrespective of substrate type, maintaining appropriate chemical characteristics—particularly root-zone pH and electrical conductivity—is essential for optimal nutrient availability and plant performance in soilless flower crop production. Most ornamental species achieve best results at substrate pH values in the range of 5.5 to 6.5, within which the solubility of iron, manganese, and other micronutrients is adequate for plant requirements whilst the solubility of potentially phytotoxic elements such as aluminium is restricted. Deviations outside this range are among the most common causes of nutrient deficiency and toxicity symptoms in commercial soilless floriculture (Mattson & Leatherwood, 2010).

Silicon supplementation represents a growing area of interest in soilless ornamental nutrition. Whilst silicon is not classified as an essential element for most plant species, it can confer significant structural and physiological benefits when supplied in adequate quantities. Mattson and Leatherwood (2010) conducted a systematic investigation of potassium silicate drench applications to several floriculture crops—including chrysanthemum and *Impatiens*—grown in peat-based substrate, and found that silicon supplementation consistently increased leaf silicon content whilst also producing commercially desirable morphological effects, including reduced stem internode elongation, increased leaf thickness, and a more compact overall plant habit. These improvements in physical quality were observed without chemical plant growth regulators, pointing to silicon supplementation as a practical and biologically sound management tool for soilless floriculture producers seeking to improve product quality whilst reducing synthetic input loads.

5. Nutrient Solution Management in Soilless Flower Production

5.1 Principles of Nutrient Solution Formulation

In soilless systems, the nutrient solution constitutes the exclusive source of mineral nutrition for crop plants, and its precise formulation is correspondingly more critical than in soil-based systems, where the soil's own nutrient reserves and buffering chemistry can partially compensate for imprecision in fertiliser application. The general design principle is to deliver all essential macro- and micro-elements at concentrations that neither restrict growth through deficiency nor cause toxicity or osmotic stress (Sambo et al., 2019). Practical guidance on nutrient solution formulation for flower crops draws on decades of empirical research in commercial greenhouse production and a growing body of physiologically grounded experimental work.

Electrical conductivity (EC) serves as the primary operational proxy for total dissolved nutrient concentration, and is routinely monitored in real time in commercial soilless facilities. For most cut flower crops, a target solution EC in the range of 1.5–2.5 dS m^{-1} is widely recommended, though optimal values differ by species, developmental stage, and ambient growing conditions. Roses, for instance, typically achieve best stem quality and flower production within a narrow EC window of approximately 1.8–2.2 dS m^{-1} (Massa et al., 2009). Solution pH, targeted at 5.5–6.5 across most flower crop species, exerts a dominant influence on the speciation and bioavailability of nutrient ions, and even modest deviations from the target range—particularly upward shifts above pH 7.0—can precipitate widespread micronutrient deficiencies through the formation of insoluble hydroxide complexes (Incrocci et al., 2017).

5.2 Macronutrient and Micronutrient Management

Nitrogen is the most abundant macronutrient in plant tissue and the most complex to manage in soilless systems. The ratio of ammonium to nitrate nitrogen in the solution influences root-zone pH and has direct physiological effects on plant growth; high ammonium supply tends to decrease rhizosphere pH and can cause ammonium toxicity symptoms in sensitive ornamental species. For cut roses, a predominantly nitrate-based nitrogen supply is generally recommended, both to maintain solution pH stability and to avoid the growth suppression and quality loss associated with ammonium accumulation (Massa et al., 2009). Potassium is critical for turgor maintenance and stomatal regulation, and in rose cut flower production, adequate pre-harvest potassium supply has been associated with superior petal turgescence and extended post-harvest vase life (Massa et al., 2009). The delivery of calcium—essential for cell wall integrity and implicated in the prevention of several physiological disorders in ornamentals—is complicated by its antagonistic interactions with potassium and magnesium for root uptake, requiring careful solution design to ensure that cation balance does not inadvertently restrict calcium availability (Sambo et al., 2019).

Micronutrient management presents additional challenges in soilless floriculture. Iron deficiency is one of the most frequently encountered nutritional problems in hydroponic flower production, often arising from solution pH drift towards alkalinity rather than from any absolute shortage of iron in the solution. Chelated iron formulations—particularly FeEDTA and FeEDDHA—are therefore standard components of soilless nutrient solutions for ornamentals, maintaining iron bioavailability across the operational pH range. Silicon supplementation through potassium silicate can improve structural quality attributes in several floriculture crops (Mattson & Leatherwood, 2010), and the role of other beneficial elements in soilless flower crop nutrition remains an active area of investigation.

5.3 Fertigation Frequency, Timing, and Automation

The frequency and temporal patterning of nutrient solution delivery profoundly affect both plant performance and the resource use efficiency of soilless systems. In drip-irrigated substrate systems, irrigation events may be triggered by time-based schedules or by substrate moisture sensors that respond continuously to volumetric water content in the rooting medium. Sensor-based scheduling confers important advantages over fixed time-interval approaches because it enables the system to respond dynamically to variation in plant water demand driven by light intensity, temperature, humidity deficit, and crop development stage, thereby reducing both over-irrigation and the leaching of nutrients beyond the root zone (Incrocci et al., 2017). Incrocci et al. (2017) reviewed contemporary trends in greenhouse fertigation management, documenting the broad shift towards sensor-integrated and computer-controlled delivery systems in commercial soilless horticulture. These precision systems improve crop performance through greater consistency of root-zone conditions and simultaneously reduce water consumption and nutrient leaching—twin outcomes that address the most pressing operational and environmental concerns of the soilless floriculture sector.

In recirculating systems, automation extends to the continuous monitoring of EC and pH in the returned solution, with compensatory injection of concentrated fertiliser stock or acid/base solutions triggered as parameters drift from target ranges. More sophisticated closed-loop systems additionally employ ion-selective electrodes or regular partial chemical analysis of recirculated solution to detect shifts in individual nutrient ratios, enabling targeted adjustment of specific element concentrations independently of total EC (Sambo et al., 2019). This level of chemical control, practically unachievable in soil-based floriculture, is one of the most powerful differentiators of advanced soilless systems.

5.4 Organic and Alternative Nutrient Sources

The emerging concept of organic or bio-organic hydroponics—in which naturally derived materials replace synthetic mineral salts as the source of plant nutrition in soilless systems—has attracted growing research and commercial interest. Shinohara et al. (2011) investigated the microbial mineralisation of organic nitrogen in hydroponic solutions, demonstrating that appropriate microbial communities could reliably transform organic nitrogen into plant-available inorganic forms, and that crop quality in organic hydroponic systems could approach that achieved with conventional mineral solutions when microbial communities were well-established. For floriculture, where certification as organically produced commands a market premium for some product categories, such approaches may hold particular commercial promise, though the reliability and speed of organic nitrogen mineralisation under the varied temperature and pH conditions of commercial soilless facilities remain important challenges to be addressed.

Thompson et al. (2007) examined the nitrogen management practices most strongly associated with nitrate leaching from intensive protected vegetable systems, identifying excess irrigation volume and infrequent, high-volume fertigation events as key contributing factors. Their findings are directly applicable to soilless floriculture, where similar nitrogen application intensities and comparable risk factors are common, and they underscore the importance of precision fertigation in minimising the environmental nitrogen footprint of commercial flower production.

6. Light Management in Soilless Flower Cultivation

6.1 Importance of Light in Controlled Environment Floriculture

Light is simultaneously the primary energy source for photosynthesis and the most critical environmental signal governing the initiation and development of flowering in most commercial ornamental species. In greenhouse and fully enclosed soilless production systems, light management encompasses the quantitative dimension—expressed as the total daily light integral (DLI, in mol m^{-2} d^{-1})—and the qualitative dimension, including spectral composition, photoperiod, and spatial uniformity of radiation distribution across the canopy. The controlled environment that makes soilless cultivation possible affords the grower a degree of dominion over the light regime that is entirely absent in open-field production, and this capacity is increasingly leveraged in advanced facilities to achieve year-round production scheduling and consistent product quality independent of season (Benke & Tomkins, 2017).

For photoperiod-sensitive ornamentals—which include a substantial proportion of commercially important cut flower and pot plant species—the ability to manipulate day length through supplemental light interruption treatments or light-excluding blackout screens is fundamental to production scheduling. Chrysanthemum, a classic short-day plant requiring day lengths of fewer than approximately 14.5 hours to initiate floral development, is commercially produced year-round globally through precisely timed photoperiodic manipulation, and this practice is entirely compatible with, and in some respects enhanced by, the controlled conditions of soilless greenhouse culture.

6.2 High-Pressure Sodium and LED Technologies

High-pressure sodium (HPS) lamps have served as the standard supplemental lighting technology in commercial greenhouse horticulture for several decades, valued for their comparatively high photon conversion efficiency, reliable long-term performance, and well-understood spectral emission characteristics. HPS fixtures emit light concentrated primarily in the yellow-orange and red portions of the visible spectrum, with limited blue output and a substantial proportion of the energy input dissipated as infrared (heat) radiation—a characteristic that necessitates adequate spacing between fixtures and canopy to prevent thermal damage and that can complicate winter climate management in well-insulated greenhouses (Morrow, 2008).

LED technology has emerged as a transformative alternative in controlled environment horticulture, offering higher electricity-to-photon conversion efficiency than HPS at current commercial standards, a substantially longer operational lifespan, negligible heat radiation from the light-emitting surface itself, and—critically for advanced horticultural applications—the capacity to produce light of precisely defined spectral composition. Morrow (2008), in a landmark early review, described LEDs as holding exceptional potential for horticultural applications because of their spectral flexibility and their suitability for close placement to crop canopies without risk of heat stress. Pattison et al. (2018) subsequently provided a comprehensive and authoritative review of LED technology for horticultural applications, contextualising the photophysical properties of LEDs within plant photobiology and demonstrating that modern commercial LED arrays had achieved photon efficiencies competitive with HPS whilst providing considerably greater spectral flexibility. Rehman et al. (2017) evaluated LED lighting as a light source for indoor plant production across a range of scenarios, concluding that whilst HPS remained the incumbent technology for many large-scale greenhouse applications at the time of their review, the accelerating improvement in LED efficacy and the declining cost of LED fixtures were rapidly closing the economic gap.

6.3 Spectral Manipulation and Flower Quality

A key and distinctive advantage of LED lighting in soilless floriculture is the ability to tailor the spectral output of supplemental light to manipulate specific aspects of plant development and product quality. Red wavelengths near 660 nm drive photosynthesis with the highest quantum efficiency within the photosynthetically active spectrum; however, a proportion of blue light (approximately 450 nm) is also required for the photomorphogenic responses that govern compact, structurally sound plant habit, appropriate leaf anatomy, and normal stomatal function. Rehman et al. (2017) reviewed evidence across multiple indoor crop systems, noting that the optimal red-to-blue photon ratio varies considerably by species and developmental stage and interacts with the absolute photon flux density being applied. These insights have direct relevance for soilless floriculture, where the programmable nature of LED arrays allows species- and stage-specific spectral regimes to be implemented in a way that is entirely impractical with broad-spectrum conventional lamps.

Beyond growth and architecture, the spectral quality of light strongly influences the accumulation of secondary metabolites that are central to the commercial value of ornamental flowers. Landi et al. (2020) reviewed the photosynthetic and secondary metabolite responses of plants to monochromatic light environments, demonstrating that blue and UV-A wavelengths are particularly potent inducers of flavonoid and anthocyanin biosynthesis—pigments responsible for the red, purple, orange, and pink colours of numerous commercially important flower crops including gerbera, petunia, and pelargonium. Their analysis suggests that LED spectra enriched in blue wavelengths during specific developmental windows may provide a practical means of enhancing flower colour intensity in soilless-grown ornamentals, offering producers a tool for differentiating premium-quality products without recourse to post-harvest treatments.

6.4 Closed-Environment Plant Factories and Floriculture

The integration of LED technology with soilless culture in fully enclosed, artificially lit plant factories offers novel possibilities for flower crop production that are not accessible in conventional greenhouse settings. In such facilities, daylength, light spectrum, intensity, and timing are all fully programmable, enabling the grower to implement production protocols that are completely independent of external seasonal conditions, latitude, and weather. Kozai (2013) described the operational logic of closed plant production systems with artificial lighting, documenting substantially higher resource use efficiencies in terms of water and land per unit of product, and noting that energy consumption per unit area, whilst high in absolute terms, can be offset for high-value crops by the intensity and quality of production achievable. Graamans et al. (2018) compared resource use efficiency between plant factories and conventionally glazed greenhouses, confirming that plant factories offer superior water and land use efficiency but at significantly higher energy costs per kilogramme of product under current northern European energy price structures. For high-value ornamentals such as orchids, chrysanthemums, and speciality cut flowers—where the revenue per unit of energy consumed is substantially higher than for commodity food crops—the economics of fully enclosed production are correspondingly more favourable, and several commercial initiatives in Japan, South Korea, and the Netherlands have demonstrated the feasibility of year-round soilless flower production under purely artificial light.

7. Water Use Efficiency and Irrigation Management in Soilless Floriculture

7.1 Water Consumption and the Case for Soilless Efficiency

Water use efficiency is perhaps the most frequently cited operational advantage of soilless production relative to soil-based cultivation. In conventional soil-irrigated floriculture, substantial fractions of applied irrigation water are lost through deep percolation beyond the functional root zone, surface evaporation from the soil matrix, and runoff, with only a modest fraction transpired by the crop or incorporated into plant tissue. Soilless systems, by delivering water directly to the root zone within a defined, bounded substrate volume, eliminate most of these non-productive pathways. The differences in water consumption between production systems can be striking. Barbosa et al. (2015) demonstrated in a rigorous comparative analysis that hydroponic lettuce production required approximately 20 litres of water per kilogramme of fresh produce, compared with approximately 250 litres for conventionally irrigated field production—a difference of roughly 12-fold—attributable to the elimination of soil drainage losses and the recirculation of unused solution. Whilst lettuce differs markedly from cut flower species in biology and production practice, the underlying hydraulic efficiency principles are system-level properties that apply similarly to soilless floriculture, where the financial premium of the crop makes the capital investment in water-efficient infrastructure particularly justifiable.

7.2 Sensor-Based Irrigation Scheduling

Significant advances in substrate moisture sensor technology over the past two decades have enabled irrigation management in soilless floriculture to move beyond empirical time-based scheduling towards genuinely demand-responsive, closed-loop control. Capacitance and time-domain reflectometry sensors embedded within the rooting substrate provide continuous, real-time estimates of volumetric water content, and when integrated with programmable irrigation controllers they allow delivery to be matched closely to actual crop demand rather than fixed to predetermined time intervals. Incrocci et al. (2017) reviewed the adoption of such sensor-integrated control systems across protected horticulture, documenting consistent reductions in both total water applied and nutrient leaching losses relative to conventional calendar-based scheduling, without compromise to crop growth or quality. These improvements arise because sensor-driven systems curtail irrigation as soon as the substrate reaches a target moisture threshold, preventing the excess drainage events that characterise time-based management and that are responsible for the majority of nitrogen and phosphorus losses from open soilless systems. The practical significance of this approach is particularly pronounced in soilless ornamental production, where coir and peat-based substrates exhibit water-holding characteristics that are sensitive to particle size distribution, degree of compaction, and prior wetting history, making uniform delivery under a fixed schedule inherently unreliable.

7.3 Recirculating Systems and Environmental Performance

Closed or recirculating soilless systems represent the most resource-efficient configuration for commercial soilless floriculture, capturing drainage solution from the root zone and returning it to the irrigation supply following any necessary treatment and analytical adjustment. The environmental performance advantages of recirculating systems extend beyond water savings to encompass substantially reduced nutrient discharge, addressing one of the most significant environmental externalities associated with intensive greenhouse floriculture—the eutrophication of receiving water bodies through nitrate and phosphate leaching from open system drainage (Gruda et al., 2019). As recirculating systems return unused nutrients to the crop, the proportion of applied fertiliser that is productively assimilated by plants is markedly higher than in open systems, reducing both the input cost and the environmental burden of nutrient management.

The principal technical challenge of closed soilless systems is the risk of pathogen accumulation and recirculation. Oomycete pathogens—particularly *Pythium* spp. and *Phytophthora* spp.—are ubiquitous in water-based plant production environments and can propagate rapidly through recirculated solution, causing devastating epidemics of root rot and crown rot in susceptible ornamental crops if not actively managed (Paulitz & Bélanger, 2001). Disinfection of recirculated solution—typically accomplished through slow sand filtration, UV irradiation, heat pasteurisation, ozonation, or copper ionisation—is therefore an essential operational component of any closed soilless system in floriculture (Paulitz & Bélanger, 2001). The capital and operational costs associated with these disinfection technologies represent a meaningful barrier to adoption, particularly for smaller-scale producers for whom the investment may be difficult to justify against projected savings in water and fertiliser inputs alone.

8. Application to Major Flower Crops

8.1 Rose

The cut rose (*Rosa* × *hybrida*) ranks among the most economically significant flower crops worldwide and is produced at commercial scale in soilless systems across a wide range of geographies, from the heated glasshouses of the Netherlands to the high-altitude greenhouse complexes of Kenya and Ethiopia. Rockwool slabs and, increasingly, coconut coir bags serve as the dominant substrates in contemporary Dutch rose production, with drip irrigation delivering a nutrient solution typically maintained at an EC of 1.8–2.2 dS m^{-1} (Massa et al., 2009). One of the most important management challenges specific to rose soilless culture is the progressive accumulation of sodium in recirculating systems, a consequence of sodium being poorly absorbed by rose roots. Massa et al. (2009) conducted a mechanistically grounded study of the interactions between sodium concentration and the uptake kinetics of nitrate and potassium by rose plants in a drip-irrigated soilless system, demonstrating that elevated sodium concentration in the root zone suppressed the uptake of both macronutrients in a manner consistent with competitive cation inhibition. The Michaelis–Menten modelling framework they applied provided a quantitative basis for understanding and managing sodium-induced nutritional stress in rose production—a contribution of direct practical significance for commercial operations using recirculated or moderate-salinity water sources.

Early simulation modelling work by Lieth and Pasian (1991) laid important theoretical groundwork for understanding rose photosynthesis and development in controlled environments, and subsequent decades of research and commercial refinement have produced detailed protocols for managing the soilless rose crop across its production cycle. The choice of substrate in soilless rose production influences not only plant nutrition and water relations but also the incidence and severity of root-zone pathogen infections, particularly those caused by *Pythium* and *Phytophthora* spp. Coir substrates have been associated in some studies with more biologically diverse and pathogen-suppressive root-zone microbial communities than rockwool, potentially contributing to the reduced disease pressure sometimes observed in coir-grown rose crops (Paulitz & Bélanger, 2001).

8.2 Chrysanthemum

Chrysanthemum (*Chrysanthemum × morifolium*) is among the world's most widely cultivated cut flowers and is additionally produced in very large volumes as a potted ornamental. As a facultative short-day plant, chrysanthemum production scheduling depends fundamentally on photoperiod management—a technique that has been refined over several decades and that is entirely compatible with greenhouse soilless production environments. In soilless systems, chrysanthemum has been successfully cultivated in NFT channels, rockwool slabs, coir bags, and perlite-filled troughs. Substrate composition and physical characteristics significantly affect root development and disease incidence in this crop, with air-filled porosity and hydraulic conductivity of the medium representing particularly important determinants of root architecture and final floral stem quality (Gruda, 2019).

The colour, size, and structural quality of chrysanthemum flowers are particularly responsive to light quality during the floral development period, making the combination of soilless culture with LED lighting a promising area for applied research. As discussed in Section 6.3, the capacity to manipulate anthocyanin accumulation in chrysanthemum petals through blue and UV wavelength enrichment (Landi et al., 2020) suggests practical opportunities for producing flowers with enhanced or novel colour expression in soilless-controlled environments. Nutrient management considerations for chrysanthemum in soilless systems broadly parallel those for rose, with particular attention required to calcium supply—to prevent tipburn disorders in some cultivars—and to the nitrogen form ratio, which affects solution pH stability and root health.

8.3 Gerbera

Gerbera (*Gerbera jamesonii* Bolus) is an internationally important cut flower species whose large, vibrantly coloured composite floral heads make it among the most recognisable of commercial ornamentals. Gerbera is widely cultivated in soilless systems across the Netherlands, Spain, Italy, and in producing regions throughout Africa and Latin America, predominantly using rockwool slabs or coconut coir bags as the rooting medium and drip-irrigated nutrient solution maintained at an EC of approximately 1.5–2.0 dS m^{-1}. Gerbera is notably sensitive to waterlogging and root asphyxiation—more so than rose or chrysanthemum—meaning that substrate air-filled porosity is a particularly critical parameter; overly moisture-retentive substrates in gerbera soilless systems readily predispose the root system to *Phytophthora* crown rot, one of the most economically damaging diseases of commercial gerbera crops worldwide (Paulitz & Bélanger, 2001).

The interaction between soilless nutrition and commercially important quality attributes in gerbera has been an active area of investigation. Calcium and boron adequacy in the nutrient solution is essential for normal stem elongation and the prevention of hollow stem disorder—a post-harvest quality problem in which the aerial stem loses structural integrity, reducing vase life and the commercial grade of harvested stems. Potassium supply influences petal colour intensity and stem mechanical strength. The electrical conductivity of the nutrient solution in gerbera production must be managed within a relatively narrow optimal window: whilst moderate EC can improve stem rigidity and potentially reduce susceptibility to *Botrytis*, excessive salinity impairs flower size and root function (Savvas & Gruda, 2018; Gruda, 2019).

8.4 Phalaenopsis and Other Orchids

The *Phalaenopsis* (moth orchid) group represents one of the commercially most important segments of the global potted plant market, with production concentrated in the Netherlands, Taiwan, and South Korea. As naturally epiphytic plants, *Phalaenopsis* species require an exceptionally coarse, open-structured substrate that provides very high air-filled porosity to accommodate their aerial root physiology, under which roots perform both water and mineral absorption alongside a degree of photosynthetic activity facilitated by their chlorophyll-containing outer tissues. The soilless management of Phalaenopsis differs fundamentally from that of terrestrial cut flower crops in that substrate physical properties—particularly the maintenance of very high air-filled porosity throughout the production cycle—take precedence over chemical buffering capacity or water retention. Bark-based substrates incorporating fir or pine bark in coarse grades, alone or in combination with perlite or coconut husk chips, represent the current commercial standard for Phalaenopsis soilless production, as their open macropore structure accommodates the gas-exchange demands of epiphytic roots whilst preventing the anaerobic conditions that rapidly induce root necrosis in this genus (Sambo et al., 2019). Automated fertigation—either through periodic sub-irrigation flooding of the substrate or low-volume drip application of dilute nutrient solution at electrical conductivity levels typically well below those used for terrestrial ornamentals—is increasingly replacing manual watering in large-scale facilities, improving both application consistency and labour efficiency.

Beyond *Phalaenopsis*, the Orchidaceae family encompasses numerous commercially cultivated genera—*Cymbidium*, *Dendrobium*, *Cattleya*, and *Oncidium* among them—each with distinct substrate requirements reflecting the diversity of natural habitats from which they originate. Research on soilless culture optimisation for these genera remains considerably less extensive in the peer-reviewed literature than for major cut flower crops, representing a notable gap in the scientific knowledge base of the ornamental horticulture sector.

8.5 Pelargonium and Herbaceous Ornamentals

Pelargonium species (zonal and ivy-leaved geraniums) are among the most commercially important bedding and container plants globally, and are produced at scale in soilless substrate systems—predominantly peat-based media or peat-substitute mixtures incorporating coir and composted bark. The work of Conversa et al. (2015) on the growth and flowering of *Pelargonium zonale* in biochar-amended soilless media provides one of the more detailed species-specific analyses of novel substrate effects on a commercially important flower crop, and demonstrates that the response to growing medium amendments is not straightforwardly predictable from substrate physical properties alone but involves interactions with the fertility programme and the biological state of the substrate. The implication for commercial producers is that any transition to biochar-containing or novel substrate formulations should be accompanied by careful empirical validation under the specific crop, system, and environmental conditions of each operation.

Among the broader category of herbaceous annuals and perennials grown as potted ornamentals or cut flowers—including *Impatiens*, *Begonia*, petunia, *Eustoma grandiflorum*, and *Anthurium*—many are produced commercially in soilless peat-based or coir-based systems, often in large-scale container nurseries with automated irrigation. The silicon supplementation research of Mattson and Leatherwood (2010) demonstrated improvements in structural quality for soilless-grown *Impatiens*, confirming broader applicability across the herbaceous ornamental category. Collectively, the evidence from these diverse crops points to the versatility and adaptability of soilless cultivation across the floriculture spectrum, whilst also highlighting the need for species-specific optimisation of substrate, nutrition, and environmental management protocols.

9. Post-Harvest Quality and Vase Life of Soillessly Grown Flowers

9.1 Pre-Harvest Nutrition and Post-Harvest Performance

The vase life and overall post-harvest quality of cut flowers are determined by the interaction of a large number of pre- and post-harvest variables, and the management of the crop in the days leading up to harvest is increasingly recognised as one of the strongest determinants of post-harvest longevity. In soilless systems, the precision with which nutrient solution composition and concentration can be managed during the final stages of crop growth offers a degree of pre-harvest quality conditioning that is fundamentally unachievable in soil-based production. The balance between nitrogen, potassium, and calcium in the nutrient solution during the last week to ten days before harvest has been shown to affect stem mechanical strength, petal turgescence, susceptibility to *Botrytis cinerea* infection, and the rate of ethylene-mediated senescence in cut roses—with potassium-adequate plants consistently displaying superior vase performance compared with those grown under potassium-limited conditions (Massa et al., 2009). Strategic reduction of nitrogen supply and elevation of potassium concentration in the final pre-harvest period is increasingly practised in commercial soilless rose production as a means of improving durability in the post-harvest supply chain.

9.2 Root Health, Stem Water Uptake, and Pathogen Status

One of the less frequently quantified but practically significant advantages of soilless floriculture in relation to post-harvest quality concerns the root health status of harvested plants. Root rot caused by *Pythium*, *Phytophthora*, and related organisms reduces not only yield but also the hydraulic competence of infected stem vascular tissue, impairing water uptake after harvest and shortening vase life. Stems harvested from plants cultivated in well-managed soilless systems—where root health is maintained through pathogen-free substrate and, in closed systems, treated recirculated solution—characteristically exhibit more efficient stem water uptake and superior turgescence at harvest than stems from plants compromised by soil-borne root diseases (Paulitz & Bélanger, 2001). Whilst the magnitude of this effect varies with species and management practice, it contributes to the overall superiority of post-harvest performance that is frequently observed for soillessly produced flowers in controlled commercial comparisons.

9.3 Water Quality in Production and Post-Harvest

The quality of source water used in both soilless production and post-harvest vase solutions influences cut flower longevity in ways that intersect with production system choice. High concentrations of fluoride are phytotoxic to sensitive species—gerbera being particularly susceptible—and can cause premature petal discolouration and stem collapse. Elevated sodium and boron in irrigation water can progressively accumulate in recirculating systems and damage root membranes, impairing stem hydraulics even before harvest. The capacity of soilless operators to use purified, softened, or reverse-osmosis-treated water as the base for nutrient solutions—adjusting the starting chemistry to achieve the target nutrient profile precisely—allows producers to eliminate water quality–related post-harvest problems more effectively than is possible for producers reliant on soil-based irrigation from variable surface or groundwater sources (Sambo et al., 2019). This quality control advantage is particularly valuable in export-oriented floriculture operations, where consistent post-harvest performance is a commercial prerequisite for maintaining retail relationships in distant markets.

10. Sustainability, Environmental Considerations, and Economic Aspects

10.1 Environmental Footprint of Soilless Floriculture

The environmental performance of both conventional and soilless floriculture has attracted growing regulatory and scientific scrutiny, with particular concern directed at pesticide use, fertiliser runoff, carbon emissions from energy-intensive climate control, and the environmental costs of long-distance supply chains connecting tropical producing regions with European and North American consumer markets. Soilless production systems, whilst demonstrably more efficient than soil-based cultivation in terms of water and nutrient use, are not environmentally neutral: the energy demand of greenhouse heating and artificial lighting, the resource cost of producing mineral substrates, and the disposal burden of spent growing media all constitute genuine environmental liabilities that must be assessed in any comprehensive comparative analysis.

Gruda et al. (2019) examined the environmental impacts of protected horticulture—including soilless systems—in a wide-ranging review, identifying the transition to recirculating nutrient systems, the substitution of peat with renewable substrates, the adoption of LED lighting, and the integration of renewable energy sources for greenhouse heating and electricity as the most impactful available strategies for reducing the environmental footprint of soilless crop production. Their analysis emphasised that the environmental credentials of soilless floriculture are highly context-dependent, varying substantially with energy source, system configuration, and substrate choice. The transition from HPS to LED supplemental lighting represents one of the most tractable single interventions for reducing the direct carbon emissions of greenhouse floriculture operations (Pattison et al., 2018), given that supplemental lighting constitutes a significant fraction of total energy consumption in year-round greenhouse flower production in temperate climates.

10.2 Circular Economy and Waste Reduction

The growing emphasis on circular economy principles within European agricultural and environmental policy has given renewed impetus to efforts within soilless floriculture to close nutrient and material loops. The recirculation of nutrient solution in closed soilless systems is the most obvious expression of this principle—minimising fertiliser losses to the environment whilst also reducing input costs. Additionally, spent organic growing media from floriculture operations—coir bags, composted bark substrates, and peat-containing mixes—can in principle be recovered and repurposed as soil amendments or composted to release nutrients and organic matter back into the agricultural cycle, contributing to soil carbon restoration and reducing dependence on virgin raw materials (Gruda, 2019). Emerging research on the integration of floriculture waste streams into biogas production or composting systems is beginning to provide a more complete picture of the circular economy potential within the sector, though commercial implementation at scale remains limited.

10.3 Economic Considerations

The economic viability of soilless floriculture ultimately rests on a balance between the capital and operational costs of soilless infrastructure—including substrate, irrigation systems, climate control, and automation—and the quality premiums, yield improvements, or scheduling efficiencies that soilless production achieves relative to soil-based alternatives. For high-value species such as cut roses, *Phalaenopsis* orchids, and specialty gerberas, the commercial value of improvements in stem quality, production scheduling flexibility, and reduced disease losses is generally sufficient to justify the additional investment. For lower-value herbaceous annuals, the economic calculation is more sensitive to input costs and the level of automation achievable (Benke & Tomkins, 2017).

The progressive decline in the cost of sensor hardware, data connectivity infrastructure, and automated control systems has meaningfully reduced the technical complexity and skilled labour requirements of operating advanced soilless systems, lowering barriers to adoption for a broader range of producer scales. The integration of precision irrigation, pH/EC control, climate management, and LED lighting within unified programmable control platforms—the technological core of what is increasingly marketed as the 'smart greenhouse'—enables a level of production management consistency that would require disproportionate labour investment to achieve manually (Sambo et al., 2019). These developments are progressively improving the economic accessibility of high-performance soilless floriculture, and the evidence base suggests that the trajectory of adoption will continue upward in the coming decade.

11. Challenges and Future Perspectives

11.1 Crop-Specific Knowledge Gaps

Despite the considerable progress reviewed here, important knowledge gaps remain across the floriculture spectrum. Research on soilless production of the major commercial crops—rose, chrysanthemum, gerbera, and *Phalaenopsis*—is relatively mature, but systematic, peer-reviewed investigation of soilless culture optimisation for numerous economically significant minor and speciality ornamental species remains sparse. This applies particularly to tropical cut flower genera including *Heliconia*, *Alpinia*, and *Anthurium*; to premium specialty cut flowers such as *Eustoma grandiflorum* and *Alstroemeria*; and to bulbous ornamentals produced under forcing protocols. The absence of crop-specific soilless culture data for these species means that producers must frequently adapt recommendations developed for related, better-studied crops or rely on proprietary commercial protocols rather than the peer-reviewed evidence base—an unsatisfactory situation that current research investment does not appear to be systematically addressing.

11.2 Climate Change and Adaptation in Soilless Floriculture

Climate change presents compounding and intersecting challenges for floriculture globally. Rising baseline temperatures and the increasing frequency of extreme heat events will raise cooling energy demands in enclosed soilless facilities and may affect the thermoperiodic flowering responses of temperature-sensitive ornamental species. Altered precipitation patterns and increasing freshwater scarcity in key producing regions will intensify competition for irrigation water and may elevate the dissolved ion concentrations in available water sources—a particularly relevant concern for recirculating soilless systems susceptible to sodium accumulation. Soilless systems, by virtue of the environmental control they typically afford, offer greater adaptability to some aspects of climate change than open-field production, but the energy and infrastructure costs of maintaining optimal growing conditions in a warming climate represent an escalating constraint that requires proactive management. Research on passive cooling strategies for soilless facilities, the development of heat-tolerant ornamental cultivars suited to soilless production, and the economic integration of renewable energy supplies into floriculture operations are all priority areas for future investigation (Gruda et al., 2019).

11.3 Digitisation, Precision Agriculture, and Artificial Intelligence

The convergence of soilless horticulture with digital sensing, IoT connectivity, machine learning, and robotic automation defines perhaps the most transformative frontier of precision floriculture. Real-time, continuous monitoring of photosynthetically active radiation, canopy microclimate, substrate moisture, and individual ion concentrations in nutrient solutions—combined with predictive crop growth models and adaptive control algorithms—offers the prospect of production environments in which quality objectives and resource use targets are simultaneously optimised in response to live plant and environmental data (Sambo et al., 2019). The application of computer vision and deep-learning algorithms for non-destructive assessment of floral quality—including colour uniformity, stem length and straightness, and blemish detection—alongside the development of robotic harvesting and packaging systems tuned for delicate floral stems, is beginning to reshape the labour economics of soilless floriculture. The controlled and physically standardised nature of soilless production environments is inherently more amenable to algorithmic management and robotic operation than the variable and complex conditions of soil-based floriculture, and this structural advantage is likely to accelerate the integration of advanced digital technologies within the sector.

11.4 Sustainable Substrate Innovation

The development of growing media that perform comparably to the best mineral or coir-based substrates whilst satisfying contemporary sustainability criteria remains an active and commercially important research frontier. Biochar from diverse feedstocks, wood fibre from forestry residues, spent mushroom substrate, digestate from anaerobic digestion, and novel hybrid materials incorporating biopolymers or aerogel components all represent potential substrate innovations under current investigation, though none has yet demonstrated the combination of consistent physical performance, biological safety, commercial scalability, and favourable end-of-life properties needed to displace established substrates across the full diversity of soilless floriculture applications. The incorporation of designed microbial communities—including mycorrhizal fungi, plant growth-promoting rhizobacteria, and biological control agents—into substrate formulations represents a further dimension of innovation with evidence-based potential for improving nutrient use efficiency, stress tolerance, and disease resistance in soilless flower crops (Conversa et al., 2015; Paulitz & Bélanger, 2001).

11.5 Policy, Market Access, and Upscaling

The scale-up of soilless floriculture—from research and artisanal commercial operations to large-scale urban and peri-urban production facilities—faces regulatory, logistical, and financial obstacles that vary substantially between jurisdictions. Planning permissions for large enclosed growing structures, regulations governing the use of recirculated water and waste-derived substrates in ornamental production, and policies on energy subsidy and carbon pricing all directly shape the business environment for soilless floriculture investment. Alignment between scientific communities, industry bodies, and policy-making institutions is necessary to create regulatory frameworks that reward environmental performance—particularly with respect to closed nutrient systems and low-emission energy choices—whilst maintaining the safety and quality standards that consumers and importers require.

12. Conclusions

Soilless cultivation has fundamentally restructured the technical and commercial possibilities of flower crop production over the past several decades. The evidence reviewed in this article demonstrates, across a range of system types, crop species, and operational contexts, that soilless methods can deliver superior product quality, more reliable production scheduling, more efficient use of water and mineral nutrients, and greater freedom from soil-borne disease relative to conventional soil-based floriculture. The advances in growing substrates—including the development and commercial mainstreaming of coconut coir alternatives to peat and rockwool, and the emerging role of biochar-incorporated media—reflect a sector that is actively reconciling performance demands with environmental sustainability obligations. Nutrient solution management has evolved from largely empirical practice towards scientifically grounded precision, supported by continuous monitoring technologies and sophisticated automated control systems that maintain the root-zone chemical environment within narrow optimal ranges. LED lighting technology has added a new and powerful dimension to the soilless floriculture toolbox, enabling spectral manipulation of flowering time, plant architecture, and pigment accumulation in ways that were previously unachievable, and whose commercial potential in precision ornamental production remains far from fully explored.

The application of soilless systems to the major commercial flower crops—rose, chrysanthemum, gerbera, orchid, and pelargonium—has been reviewed in detail, revealing both the considerable progress achieved in species-specific optimisation and the many crop categories for which the evidence base remains thin. Post-harvest quality benefits associated with soilless production—stemming from superior root health, controlled pre-harvest nutrition, and water quality management—represent an underappreciated but commercially significant advantage of the approach, particularly for export-oriented operations. The sustainability assessment of soilless floriculture is nuanced: the water and nutrient efficiency advantages are clear and well-evidenced, but the energy costs of climate control and artificial lighting demand continued innovation in renewable energy integration and energy-efficient technology adoption. The trajectory of development in the field—towards greater automation, more intelligent sensing, more sustainable substrate materials, and progressively tighter integration with circular economy frameworks—suggests that soilless cultivation will deepen its central role in global floriculture over the coming decades.

13. Limitations

This review is subject to several important limitations that should be considered when interpreting its findings and conclusions. The literature synthesis is inherently constrained by the publication landscape of the field: peer-reviewed, English-language research on soilless floriculture is disproportionately concentrated within European—particularly Dutch, Italian, and German—production contexts, reflecting the geographic centres of greenhouse horticulture research. This means that insights derived from major producing regions in sub-Saharan Africa, South America, and South and Southeast Asia, where significant commercial flower crop production occurs under conditions quite different from those characterised in European research, are comparatively underrepresented in this review. The narrative methodology, though appropriate for the integrative purposes of this article, does not provide the same systematic transparency regarding literature selection as a formal systematic review protocol, and introduces the possibility of subjective emphasis in the allocation of discussion space to different topics and findings. Additionally, the field is advancing rapidly, and research published subsequent to the search window will inevitably extend and modify some of the perspectives presented here. The comparative economic analyses cited in this review are sensitive to regional energy prices, labour costs, and market conditions that vary substantially across geographies and are subject to ongoing change, and the conclusions regarding economic feasibility should therefore be treated as indicative rather than universally applicable. Finally, whilst this review aimed to cover the major commercial flower crop genera in reasonable depth, the diversity of commercially cultivated ornamental species is vast, and many significant crops receive limited or no attention in the peer-reviewed soilless culture literature and therefore also in this review.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Competing Interests

Authors have declared that no competing interests exist.

References

Abad, M., Noguera, P., Puchades, R., Maquieira, A., & Noguera, V. (2002). Physico-chemical and chemical properties of some coconut coir dusts for use as a peat substitute for containerised ornamental plants. *Bioresource Technology*, *82*(3), 241–245. https://doi.org/10.1016/S0960-8524(01)00189-4

Barbosa, G. L., Gadelha, F. D. A., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., Wohlleb, G. M., & Halden, R. U. (2015). Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional outdoor production systems. *International Journal of Environmental Research and Public Health*, *12*(6), 6879–6891. https://doi.org/10.3390/ijerph120606879

Benke, K., & Tomkins, B. (2017). Future food-production systems: Vertical farming and controlled-environment agriculture. *Sustainability: Science, Practice and Policy*, *13*(1), 13–26. https://doi.org/10.1080/15487733.2017.1394054

Conversa, G., Bonasia, A., Lazzizera, C., Scialpi, A., & Elia, A. (2015). Influence of biochar, mycorrhizal inoculation, and fertilizer rate on growth and flowering of *Pelargonium* (*Pelargonium zonale* L.) plants. *Frontiers in Plant Science*, *6*, 429. https://doi.org/10.3389/fpls.2015.00429

Gebreegziher, W. G. (2023). Soilless culture technology to transform vegetable farming, reduce land pressure and degradation in drylands. *Cogent Food & Agriculture*, *9*(2), 2265106.

Glaser, B., Lehmann, J., & Zech, W. (2002). Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal—A review. *Biology and Fertility of Soils*, *35*(4), 219–230. https://doi.org/10.1007/s00374-002-0466-4

Graamans, L., Baeza, E., van den Dobbelsteen, A., Tsafaras, I., & Stanghellini, C. (2018). Plant factories versus greenhouses: Comparison of resource use efficiency. *Agricultural Systems*, *160*, 31–43. https://doi.org/10.1016/j.agsy.2017.11.003

Green, B. N., Johnson, C. D., & Adams, A. (2006). Writing narrative literature reviews for peer-reviewed journals: Secrets of the trade. *Journal of Chiropractic Medicine*, *5*(3), 101–117. https://doi.org/10.1016/S0899-3467(07)60142-6

Gruda, N. (2019). Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems. *Agronomy*, *9*(6), 298. https://doi.org/10.3390/agronomy9060298

Gruda, N. S. (2022). Advances in Soilless Culture and Growing Media in Today's Horticulture—An Editorial. *Agronomy*, *12*(11), 2773. https://doi.org/10.3390/agronomy12112773

Gruda, N., Bisbis, M., & Tanny, J. (2019). Influence of climate change on protected cultivation: Impacts and sustainable adaptation strategies—A review. *Journal of Cleaner Production*, *225*, 481–495. https://doi.org/10.1016/j.jclepro.2019.03.210

Incrocci, L., Massa, D., & Pardossi, A. (2017). New trends in the fertigation management of irrigated vegetable crops. *Horticulturae*, *3*(2), 37. https://doi.org/10.3390/horticulturae3020037

Kozai, T. (2013). Resource use efficiency of closed plant production system with artificial light: Concept, estimation and application to plant factory. *Proceedings of the Japan Academy, Series B*, *89*(10), 447–461. https://doi.org/10.2183/pjab.89.447

Lakhiar, I. A., Gao, J., Syed, T. N., Chandio, F. A., & Buttar, N. A. (2018). Modern plant cultivation technologies in agriculture under controlled environment: A review on aeroponics. *Journal of Plant Interactions*, *13*(1), 338–352. https://doi.org/10.1080/17429145.2018.1472308

Landi, M., Zivcak, M., Sytar, O., Brestic, M., & Allakhverdiev, S. I. (2020). Plasticity of photosynthetic processes and the accumulation of secondary metabolites in plants in response to monochromatic light environments: A review. *Biochimica et Biophysica Acta – Bioenergetics*, *1861*(2), 148131. https://doi.org/10.1016/j.bbabio.2019.148131

Lieth, J. H., & Pasian, C. C. (1991). A model for net photosynthesis of rose leaves as a function of photosynthetically active radiation, leaf temperature, and leaf age. *Journal of the American Society for Horticultural Science*, *116*(4), 679–685. https://doi.org/10.21273/JASHS.115.3.486

Massa, D., Mattson, N. S., & Lieth, H. J. (2009). Effects of saline root environment (NaCl) on nitrate and potassium uptake kinetics for rose plants: a Michaelis–Menten modelling approach. Plant and soil, 318(1), 101-115. https://doi.org/10.1007/s11104-008-9821-z

Mattson, N. S., & Leatherwood, W. R. (2010). Potassium silicate drenches increase silicon content and enhance certain quality attributes of several floriculture crops grown in a peat-based substrate. *HortScience*, *45*(1), 43–47. https://doi.org/10.21273/HORTSCI.45.1.43

Morrow, R. C. (2008). LED lighting in horticulture. *HortScience*, *43*(7), 1947–1950. https://doi.org/10.21273/HORTSCI.43.7.1947

Pattison, P. M., Tsao, J. Y., Brainard, G. C., & Bugbee, B. (2018). LEDs for photons, physiology and food. *Nature*, *563*, 493–500. https://doi.org/10.1038/s41586-018-0706-x

Paulitz, T. C., & Bélanger, R. R. (2001). Biological control in greenhouse systems. *Annual Review of Phytopathology*, *39*, 103–133. https://doi.org/10.1146/annurev.phyto.39.1.103

Rehman, M., Ullah, S., Bao, Y., Wang, B., Peng, D., & Liu, L. (2017). Light-emitting diodes: Whether an efficient source of light for indoor plants? *Environmental Science and Pollution Research*, *24*(32), 24743–24752. https://doi.org/10.1007/s11356-017-0333-3

Sambo, P., Nicoletto, C., Giro, A., Pii, Y., Valentinuzzi, F., Mimmo, T., Lugli, P., Orzes, G., Mazzetto, F., Astolfi, S., Terzano, R., & Cesco, S. (2019). Hydroponic solutions for soilless production systems: Issues and opportunities in a smart agriculture perspective. *Frontiers in Plant Science*, *10*, 923. https://doi.org/10.3389/fpls.2019.00923

Savvas, D., & Gruda, N. (2018). Application of soilless culture technologies in the modern greenhouse industry—A review. *European Journal of Horticultural Science*, *83*(5), 280–293. https://doi.org/10.17660/eJHS.2018/83.5.2

Shinohara, M., Aoyama, C., Fujiwara, K., Watanabe, A., Ohmori, H., Uehara, Y., & Takano, M. (2011). Microbial mineralisation of organic nitrogen into ammonium, nitrite, and nitrate in a hydroponic system. *Soil Science and Plant Nutrition 57(2):190-203*. https://doi.org/10.1080/00380768.2011.554223

Thompson, R. B., Martínez-Gaitan, C., Gallardo, M., Giménez, C., & Fernández, M. D. (2007). Identification of irrigation and N management practices that contribute to nitrate leaching loss from an intensive vegetable production system by use of a comprehensive survey. *Agricultural Water Management*, *89*(3), 261–274. https://doi.org/10.1016/j.agwat.2007.01.007

Tian, Y., Sun, X., Li, S., Wang, H., Wang, L., Cao, J., & Zhang, L. (2012). Biochar made from green waste as peat substitute in growth media for *Calathea rotundifolia* cv. Eclipse. *Scientia Horticulturae*, *143*, 10–14. https://doi.org/10.1016/j.scienta.2012.05.018

Peer-review history:
The peer review history for this paper can be accessed here:
https://pr.sdiarticle5.com/review-history/158317