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Advancing controlled environment urban agriculture: integrating LED spectral engineering and intelligent nutrient delivery systems for optimized growth across diverse crop species

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Urban controlled-environment agriculture (CEA) has emerged as a technologically advanced approach to food production that seeks to address land scarcity, climate instability, and the growing demand for fresh produce in cities. This review examined the role of smart technologies and automation, sustainability and economic performance, and the major challenges and future directions shaping urban CEA. The evidence shows that sensor-based monitoring, IoT-enabled control systems, predictive models, and automation have improved precision in environmental regulation, nutrient delivery, and light management, thereby strengthening productivity and operational consistency. Urban CEA also demonstrates important advantages in land-use efficiency, water conservation, and nutrient-use control, particularly in hydroponic and vertically stacked systems. However, these gains are moderated by high energy demand, infrastructure costs, operational complexity, and dependence on a limited range of high-value crops. The literature further reveals important research gaps in multi-crop optimization, cultivar development for indoor systems, and integrated assessments of technical, economic, and environmental performance. Policy support, regulatory alignment, and context-specific scale-up strategies remain critical to long-term viability. Urban CEA therefore holds significant promise, but its future depends on whether innovation can move beyond technical efficiency toward economically resilient, environmentally credible, and socially relevant production systems.

KEYWORDS
controlled-environment agriculture, resource use efficiency, smart farming technologies, urban agriculture, vertical farming

1 Introduction

Rapid urbanization, climate variability, shrinking arable land, and persistent pressure on food supply chains have intensified interest in production systems that can deliver fresh produce close to consumers while using land, water, and other inputs more efficiently. Urban food systems now occupy a central place in debates on food security because urban growth is reshaping agrifood demand, distribution, diet quality, and the spatial organization of production across the rural–urban continuum. Within this context, urban agriculture has gained relevance not only as a social or community-based activity, but also as a technologically advanced production strategy capable of supporting resilient and localized food systems (de Bruin and Holleman, 2023; Tefft et al., 2020). Controlled environment agriculture (CEA) has emerged as one of the most intensive forms of urban food production. CEA refers to crop production systems in which environmental variables such as light, temperature, humidity, carbon dioxide, and nutrient supply are managed to improve plant growth, quality, and year-round productivity. Greenhouses, plant factories, and indoor vertical farms represent the dominant manifestations of this approach. Their appeal lies in the capacity to decouple production from seasonal instability and to situate cultivation nearer to urban markets, thereby potentially reducing transport burdens and enhancing freshness, consistency, and supply reliability (Gómez et al., 2019; Benke and Tomkins, 2017; Heuvelink et al., 2025a).

The current phase of CEA development is increasingly defined by advances in LED lighting and soilless nutrient management. Research trends indicate that plant–light interactions, particularly under LED systems, dominate the contemporary CEA literature, reflecting the central role of spectral control in modern indoor cultivation. At the same time, hydroponic and related nutrient delivery systems have become essential for precise root-zone management, efficient input use, and rapid biomass accumulation in confined urban spaces. These developments have expanded the technical feasibility of growing not only leafy vegetables, but also herbs, fruiting crops, medicinal plants, and specialty crops under highly managed conditions (Dsouza et al., 2023; Rajaseger et al., 2023).

1.1 Urban agriculture and controlled environment agriculture

Urban agriculture encompasses the cultivation, processing, and distribution of food within and around cities. Its functions extend beyond food production to include livelihood support, greening of urban spaces, waste recycling, social cohesion, and nutritional improvement. Earlier reviews established that urban vegetable production can contribute meaningfully to food access and dietary diversity, especially where peri-urban and intra-urban land can be mobilized efficiently. However, conventional forms of urban agriculture often remain constrained by land scarcity, soil contamination, irregular water access, climatic variability, and competing urban land uses (Eigenbrod and Gruda, 2015; Tefft et al., 2020).

CEA represents a more specialized and technologically intensive branch of urban agriculture. Unlike open-field or low-input urban production, CEA is built on environmental control, engineering precision, and resource optimization. Vertical farming, in particular, has attracted attention because stacked production systems can increase output per unit ground area and support cultivation in warehouses, rooftops, containers, and repurposed urban buildings. Reviews of vertical farming have emphasized its potential to address space limitations in cities while enabling pesticide reduction, continuous production, and improved crop uniformity. At the same time, the performance of these systems depends heavily on energy management, lighting strategy, cultivar selection, and nutrient delivery design (Al-Kodmany, 2018; Benke and Tomkins, 2017; Gómez et al., 2019).

Recent scholarship has also clarified that CEA should not be treated as a single uniform technology. Research spans greenhouses, fully enclosed indoor farms, and hybrid protected systems with different production goals, environmental footprints, and economic structures. Even within indoor systems, crop responses vary markedly according to spectral composition, light intensity, photoperiod, nutrient formulation, and root-zone conditions. This heterogeneity makes it necessary to examine CEA not simply as an urban farming concept, but as a dynamic production platform in which lighting and nutrient systems interact to shape crop performance (Dsouza et al., 2023; Heuvelink et al., 2025a).

1.2 Research problem and review significance

Despite the rapid expansion of literature on urban agriculture, vertical farming, hydroponics, and LED-based crop production, the evidence base remains fragmented. One major limitation is that many studies evaluate lighting, nutrient management, or crop performance in isolation, even though plant growth in CEA depends on the simultaneous regulation of aboveground and belowground environments. Another limitation is the strong concentration of research on a narrow group of crops, particularly leafy greens such as lettuce, while broader multi-crop evidence remains comparatively limited. A recent scoping review of 610 studies found that CEA research is dominated by biological and technical themes, especially plant–light interactions, whereas socio-economic assessment, environmental evaluation, and crop diversification receive substantially less attention (Dsouza et al., 2023).

This imbalance creates an important knowledge gap for urban agriculture development. LED spectral engineering is now capable of delivering crop-specific light recipes, while intelligent nutrient delivery systems can regulate pH, electrical conductivity, oxygenation, and macro- and micronutrient supply with increasing precision. Yet there is still limited synthesis of how these two domains interact across diverse plant species. Such integration is essential because light quality can alter morphology, photosynthesis, secondary metabolism, and nutrient uptake, whereas nutrient regime can influence plant responses to light and overall resource-use efficiency. A review that brings these strands together is therefore timely and significant for both scientific understanding and practical system design (Rajaseger et al., 2023; Heuvelink et al., 2025a).

The significance of the present review also lies in its relevance to sustainable urban food systems. Claims surrounding CEA often emphasize high yields, lower water use, and production close to consumers, but concerns remain regarding energy demand, capital cost, and long-term environmental performance. A critical synthesis of LED-based lighting strategies and nutrient delivery technologies across crop groups can help clarify where the strongest evidence lies, where trade-offs persist, and which research directions are most necessary for scalable and economically viable urban agriculture (Gómez et al., 2019; Dsouza et al., 2023; Heuvelink et al., 2025a).

1.3 Aim and objectives of the review

The aim of this review is to synthesize current knowledge on the integration of LED spectral engineering and intelligent nutrient delivery systems in controlled environment urban agriculture, with emphasis on their combined effects on plant growth, yield, quality, and resource efficiency across a diverse range of crop species. The specific objectives are fourfold. First, the review examines the conceptual and technological foundations of controlled environment urban agriculture, with attention to the role of vertical farming and soilless cultivation systems in urban food production. Second, it evaluates the effects of LED spectral composition, light intensity, and photoperiod on plant physiological responses and crop performance under controlled environments. Third, it assesses the operation of hydroponic, aeroponic, aquaponic, and precision fertigation systems, with particular focus on nutrient regulation and root-zone management. Fourth, it analyzes the interaction between lighting and nutrient delivery systems across leafy vegetables, herbs, fruiting crops, medicinal plants, microgreens, and ornamental species in order to identify current knowledge gaps and future research priorities for resilient and scalable urban agriculture (Gómez et al., 2019; Dsouza et al., 2023; Rajaseger et al., 2023; Heuvelink et al., 2025a).

2 Review methodology

2.1 Review design and approach

This review was designed as a structured narrative review informed by systematic search and transparent study selection procedures. The methodological approach was chosen because the topic spans plant physiology, horticultural engineering, lighting technology, hydroponic nutrition, and urban food systems, which together generate heterogeneous evidence that is not easily amenable to meta-analysis. Structured literature reviews are particularly suitable for synthesizing broad and interdisciplinary fields, identifying conceptual patterns, and clarifying research directions when studies differ in design, crop type, environmental conditions, and measured outcomes. Reporting and study selection procedures were aligned with established evidence-synthesis guidance to improve transparency, reproducibility, and methodological consistency. The review process was further informed by frameworks commonly used in systematic and scoping reviews. The logic of evidence mapping, study identification, screening, eligibility assessment, and synthesis followed principles set out in review-methodology literature. This approach was appropriate because the available studies include experimental investigations, technical evaluations, comparative horticultural trials, and system-based studies addressing LEDs, nutrient management, and controlled environment agriculture across different crop groups.

2.2 Literature search strategy

The literature search was conducted through a comprehensive and replicable multi-stage strategy intended to capture peer-reviewed studies relevant to controlled environment urban agriculture, LED spectral engineering, and intelligent nutrient delivery systems. The search process followed the logic recommended in PRISMA 2020, beginning with identification of records, followed by removal of duplicates, title and abstract screening, full-text assessment, and final inclusion of eligible studies. Figure 1 represents a PRISMA flow diagram for the study selection process in the manuscript. The search strategy combined controlled vocabulary and free-text terms to capture variations in terminology across disciplines. Terminological differences are common in this field because relevant studies may be indexed under urban agriculture, vertical farming, plant factory systems, indoor farming, hydroponics, fertigation, nutrient solution management, light spectrum, or horticultural lighting. Multiple combinations of search terms were therefore necessary to reduce the risk of omitting relevant records and to strengthen the breadth of the review. This approach is consistent with guidance emphasizing explicit and well-documented search procedures in review studies.

2.3 Databases and sources of information

The primary sources of information included major bibliographic databases that index agricultural, biological, engineering, and environmental research. Scopus, Web of Science, ScienceDirect, PubMed, and Google Scholar are appropriate sources for this topic because they collectively cover peer-reviewed literature in plant science, controlled environment agriculture, agricultural engineering, sustainability, and food systems research. Database selection in review studies should reflect disciplinary breadth, indexing quality, and the need to capture both foundational and recent literature. Reference lists of key articles were also examined to identify additional studies that were not retrieved during the primary database search. Manual screening of cited and citing literature is widely recommended in review methodology because it improves coverage, helps locate seminal papers, and reduces database-dependent bias. This step was especially important for studies on LED spectral responses and nutrient management, where terminology and indexing practices can vary across journals and disciplines.

2.4 Search keywords and inclusion criteria

Search terms were organized around four thematic clusters: controlled environment agriculture, urban agriculture systems, LED lighting, and nutrient delivery technologies. Representative keywords included "controlled environment agriculture," "urban agriculture," "vertical farming," "indoor farming," "plant factory," "LED lighting," "light spectrum," "spectral quality," "hydroponics,"

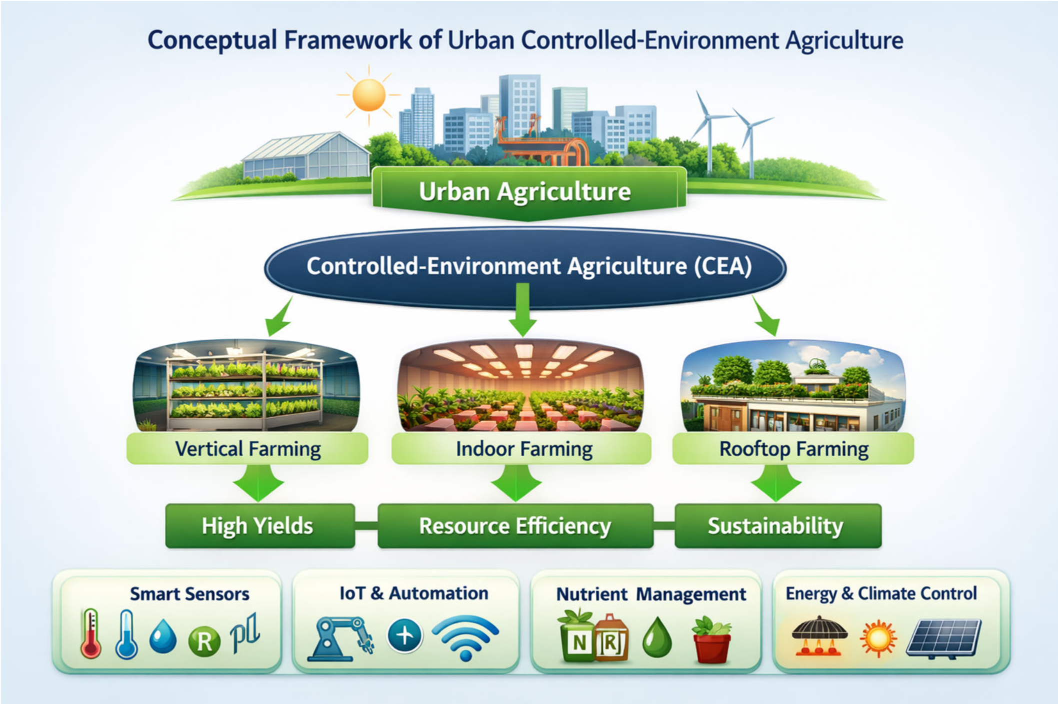

FIGURE 1
PRISMA flow diagram.

"aeroponics," "aquaponics," "fertigation," "nutrient solution," "electrical conductivity," "pH management," "crop yield," and "plant growth." Boolean operators such as AND and OR were used to combine related terms and refine retrieval. This keyword structure was intended to capture studies examining either individual system components or their interaction in crop production environments. Studies were included when they met the following criteria: they were published in peer-reviewed journals; written in English; focused on controlled environment agriculture, urban indoor farming, or closely related protected cultivation systems; examined LED lighting, nutrient delivery systems, or their interaction; and reported outcomes related to plant growth, yield, physiology, quality, or resource-use efficiency. Preference was given to recent studies in order to reflect current technological development, although foundational studies were retained when they provided essential conceptual or methodological insight. Transparent inclusion criteria are a core requirement of rigorous review design because they delimit the evidence base and support reproducibility.

2.5 Exclusion criteria

Studies were excluded when they fell outside the conceptual scope of the review or lacked sufficient relevance to the integration of lighting and nutrient management in urban CEA systems. Excluded records included conference abstracts without full papers, non-scholarly reports, opinion pieces, duplicate publications, articles not available in full text, and studies focused exclusively on open-field agriculture without controlled environmental regulation. Publications centered only on conventional greenhouse production without meaningful discussion of LED systems, nutrient control, or urban applicability were also excluded when their relevance to the review objectives was limited. Additional exclusions applied to papers with weak methodological description, insufficient outcome reporting, or highly narrow technical emphasis unrelated to plant growth or production performance. Clear exclusion criteria are important because they prevent conceptual drift, maintain coherence in the review sample, and improve the interpretability of the synthesis. This is particularly necessary in interdisciplinary topics where engineering papers, agronomic trials, and conceptual discussions may differ substantially in scope and evidentiary value.

2.6 Data extraction and synthesis

Data extraction was conducted using a structured matrix developed to record bibliographic information, study location, crop species, cultivation system, LED characteristics, nutrient management variables, experimental conditions, and principal outcomes. Extracted variables included light spectrum, light intensity, photoperiod, hydroponic or fertigation system type, pH, electrical conductivity, nutrient formulation, and reported responses such as biomass accumulation, yield, morphology, photosynthetic performance, nutrient uptake, and phytochemical quality. Standardized extraction procedures improve consistency in review studies and support a more transparent comparison of findings across heterogeneous sources. The synthesis was conducted thematically rather than statistically. Findings were organized into major analytical categories: LED spectral engineering, intelligent nutrient delivery systems, and interactions between light and nutrient management, crop-specific applications, and sustainability implications for urban agriculture. A thematic approach was appropriate because the included studies varied considerably in crop species, experimental design, treatment combinations, and outcome metrics. This form of synthesis allows integration of experimental and conceptual evidence while also revealing recurrent patterns, research gaps, and areas requiring further standardization.

3 Concept and scope of controlled environment urban agriculture

3.1 Definitions and core components

Controlled environment agriculture (CEA) refers to crop production systems in which key environmental variables are regulated to create favorable conditions for plant growth, productivity, and quality. These variables commonly include light, temperature, relative humidity, carbon dioxide concentration, irrigation, nutrient delivery, and, in many cases, root-zone oxygenation and pH. The concept covers a continuum of production systems ranging from technologically advanced greenhouses to fully enclosed indoor farms and plant factories. In urban contexts, CEA has attracted considerable attention because it enables intensive food production in locations where conventional cultivation is limited by land scarcity, contamination risks, or climatic instability (Benke and Tomkins, 2017; Gómez et al., 2019).

The core components of urban CEA include protected structures, environmental control technologies, artificial or supplemental lighting, soilless cultivation systems, and monitoring or automation platforms. Protected structures provide physical separation from outdoor variability, while control systems regulate temperature, humidity, ventilation, and carbon dioxide. LED lighting has become especially important in indoor CEA because it allows precise spectral manipulation and improved energy efficiency relative to earlier lighting technologies. Nutrient delivery systems such as hydroponics, aeroponics, and aquaponics support intensive cultivation by enabling close management of water and mineral nutrition, which is essential where soil use is impractical or undesirable. Together, these elements define CEA as an engineered production system rather than simply an urban adaptation of conventional agriculture (Gómez et al., 2019; Halliday et al., 2021).

CEA in cities is not limited to maximizing output alone; it also reflects a broader shift toward resource-efficient, spatially compact, and year-round food production. This makes the concept especially relevant to urban agriculture, where the challenge is not only to grow food within city boundaries but also to do so under constraints related to space, infrastructure, labor, and environmental quality. As a result, CEA is increasingly discussed as a strategic component of resilient urban food systems, particularly for high-value horticultural crops such as leafy greens, herbs, microgreens, and some fruiting vegetables (Al-Kodmany, 2018; Gómez et al., 2019).

3.2 Urban CEA systems: vertical farming, indoor farming, and rooftop agriculture

Vertical farming represents one of the most recognized forms of urban CEA. It generally involves multilayer crop production inside enclosed or semi-enclosed structures using artificial lighting and tightly regulated environmental conditions. The principal rationale behind vertical farming is to increase output per unit ground area while reducing dependence on seasonal climate and arable land. Reviews of the field consistently describe vertical farming as a technologically intensive model suited to dense urban settings, especially where access to land is limited and proximity to consumers offers logistical advantages (Benke and Tomkins, 2017; Al-Kodmany, 2018).

Indoor farming is closely related to vertical farming but is somewhat broader in scope because it includes single-layer and multilayer systems located in warehouses, shipping containers, repurposed industrial buildings, and plant factories. These systems rely heavily on artificial lighting, automation, and recirculating nutrient systems, allowing precise control over production conditions throughout the year. Indoor farming is particularly relevant to research on LED spectral engineering and nutrient management because plant performance in these systems depends directly on deliberate regulation of both shoot and root environments. Literature on controlled environment food production has emphasized that this level of control can improve crop uniformity, support continuous production, and reduce exposure to pests and weather-related risks, although success depends strongly on energy efficiency and system design (Gómez et al., 2019; Dsouza et al., 2023).

Rooftop agriculture occupies a distinct place within urban CEA because it uses underutilized building surfaces for food production. Rooftop systems may be open-air, protected, or greenhouse-based, and they vary substantially in technological intensity. Rooftop greenhouses are especially important within the CEA framework because they combine urban siting with protected cultivation and can potentially benefit from synergies with the host building, including heat exchange, rainwater harvesting, and improved land-use efficiency. Recent reviews show that rooftop agriculture has expanded globally as cities seek ways to integrate food production into the built environment, although structural requirements, regulatory barriers, and higher establishment costs remain important constraints (Appolloni et al., 2021; Drottberger et al., 2023b).

These three system types share a common urban logic but differ in infrastructure, operating costs, environmental performance, and crop suitability. Vertical farms and fully indoor systems offer the highest degree of environmental control, whereas rooftop agriculture often balances production goals with architectural, environmental, and social functions. Their inclusion within one conceptual framework is justified because all three seek to intensify crop production within cities through some combination of spatial innovation, environmental management, and resource optimization (Benke and Tomkins, 2017; Appolloni et al., 2021; Drottberger et al., 2023a). The principal differences among vertical farming, indoor farming, and rooftop agriculture are summarized in Table 1.

3.3 Opportunities and constraints in urban food production

Urban CEA offers several important opportunities for food production. One widely cited advantage is the ability to produce fresh horticultural crops near consumers, which can shorten supply

TABLE 1 Comparison of major urban CEA systems.

System type	Structure/ production setting	Primary light source	Water use efficiency	Relative capital cost	Typical crops	Major advantage	References
Vertical Farming	Multi-layer indoor cultivation in warehouses, containers, or purpose-built facilities	Predominantly LED artificial lighting	Very high due to recirculating hydroponics and closed systems	High to Very High	Lettuce, herbs, microgreens, leafy greens	Maximizes yield per unit land area and enables year-round production	Benke and Tomkins (2017); Al-Kodmany (2018); Pennisi et al. (2025)
Indoor Farming (Single-layer/Plant Factory)	Fully enclosed indoor facilities with complete climate control; may be single or multi-layer	LED artificial lighting	High	High	Greens, herbs, seedlings, strawberries, specialty crops	Full environmental control, biosecurity, production consistency	Gómez et al. (2019); Dsouza et al. (2023)
Rooftop Greenhouse Farming	Greenhouses located on rooftops or integrated into buildings	Sunlight with supplemental LEDs when needed	Moderate to High	Medium to High	Tomato, cucumber, lettuce, herbs, mixed vegetables	Uses underutilized urban roof space; potential building-energy synergies	Appolloni et al. (2021); Drottberger et al. (2023a)
Container Farming	Retrofitted shipping containers with compact indoor hydroponic systems	LED artificial lighting	High	Medium to High	Leafy greens, herbs, microgreens	Modular deployment, close-to-market production, rapid installation	Benke and Tomkins (2017); Gómez et al. (2019)
Hybrid Protected Systems	Semi-controlled systems combining greenhouse production with automation and sensor control	Sunlight + supplemental LED lighting	Moderate	Medium	Fruiting vegetables, ornamentals, leafy greens	Lower energy demand than fully indoor farms while retaining partial control	Gómez et al. (2019); Heuvelink et al. (2025b)

chains, reduce postharvest losses, and improve product freshness. Another advantage lies in more efficient use of land and water, especially in soilless recirculating systems. Vertical and indoor farms may also support year-round production and consistent crop quality through tighter environmental control. These characteristics make CEA particularly attractive for cities seeking greater food-system resilience under conditions of population growth, land competition, and climate uncertainty (Al-Kodmany, 2018; Gómez et al., 2019).

Resource efficiency is one of the strongest arguments in favor of urban CEA, but the evidence also shows important variation across systems. Reviews comparing urban and conventional agriculture indicate that urban production systems can reduce certain transport- and land-related pressures, yet they do not automatically guarantee lower overall environmental burdens. Performance depends on crop type, infrastructure, management intensity, and local energy sources. In rooftop systems, for example, benefits may include use of otherwise idle roof space, mitigation of urban heat effects, and building-level synergies, but these gains must be weighed against structural limitations, investment demands, and maintenance requirements (Goldstein et al., 2016; Appolloni et al., 2021; Drottberger et al., 2023a).

Several constraints continue to limit broader adoption of urban CEA. High capital requirements, substantial energy demand, technical complexity, and the need for skilled management remain persistent barriers, particularly in fully indoor systems. Economic feasibility is often sensitive to electricity cost, crop choice, and market price. Reviews of vertical farming have repeatedly noted that the promise of high productivity must be considered alongside operating costs and the environmental implications of energy-intensive production. Similar concerns arise in rooftop agriculture, where engineering requirements, access issues, and regulatory uncertainty may restrict scalability (Benke and Tomkins, 2017; Al-Kodmany, 2018; Drottberger et al., 2023a).

The scope of controlled environment urban agriculture is therefore best understood as both technological and strategic. It includes production systems designed to intensify crop cultivation within cities, but it also encompasses broader questions of sustainability, infrastructure integration, economic viability, and crop diversification. A careful examination of these opportunities and constraints is necessary for evaluating how LED spectral engineering and intelligent nutrient delivery can strengthen the performance of urban CEA across different plant species and production settings (Gómez et al., 2019; Dsouza et al., 2023). Urban controlled-environment agriculture should therefore be understood as an integrated production model that combines spatial innovation, environmental control, and resource optimization across diverse urban systems (Figure 2).

4 LED spectral engineering in controlled environment agriculture

4.1 Fundamentals of plant responses to light

Light regulates plant growth through two interconnected functions: it supplies energy for photosynthesis and acts as a developmental signal. In controlled environment agriculture (CEA), crop performance is therefore shaped not only by the amount of light received, but also by wavelength composition, photoperiod, and temporal distribution. This is particularly important in indoor farming systems where artificial lighting replaces sunlight as the

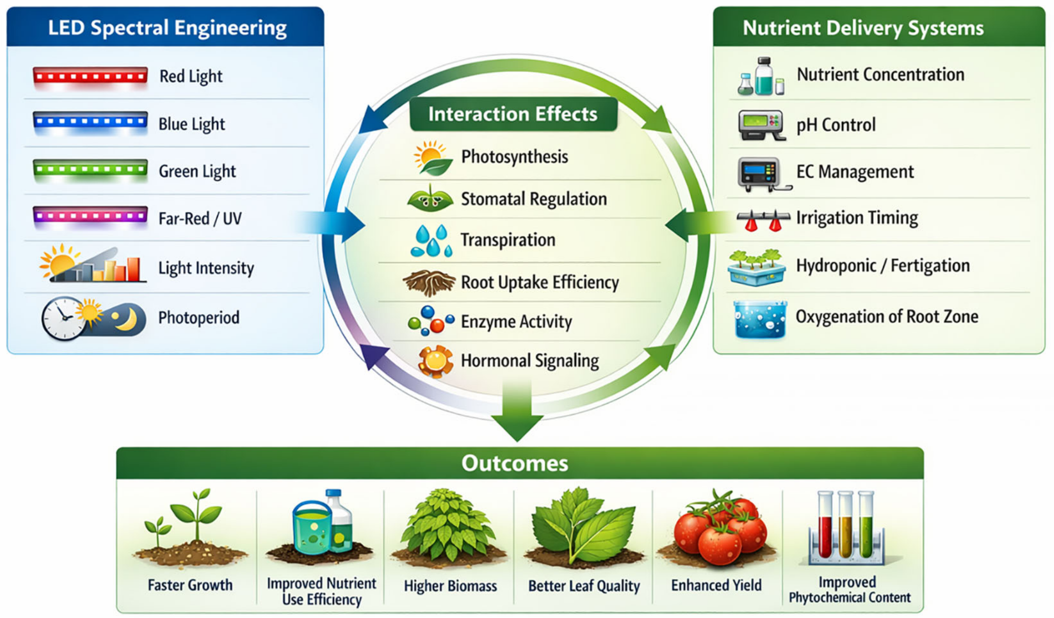

FIGURE 2
Conceptual framework of urban controlled-environment agriculture.

dominant energy source. The transition from conventional lamps to light-emitting diodes (LEDs) has greatly expanded the capacity to regulate plant environments with precision because LEDs permit targeted spectral delivery, dimming control, low radiant heat emission, and improved fixture efficiency (Gómez et al., 2019; Morrow, 2008; Zheng et al., 2019).

Plant responses to light are mediated through pigments and photoreceptors. Chlorophyll pigments absorb strongly in red and blue regions of the spectrum, supporting carbon fixation, whereas phytochromes, cryptochromes, phototropins, and UVR8 detect spectral cues that regulate developmental processes such as stem elongation, stomatal opening, flowering, leaf expansion, and secondary metabolism. These signaling pathways explain why light quality influences morphology and crop quality as much as biomass production (Ptushenko et al., 2020; Spaninks et al., 2020).

Spectral optimization in CEA is based on the recognition that plants seldom perform best under monochromatic radiation. Narrow-band red light can drive photosynthesis efficiently, yet crops grown under red light alone often display impaired morphology and reduced physiological performance. The addition of blue or broader-spectrum photons generally restores normal growth and improves functional quality. This principle has become foundational in modern LED lighting design for horticulture (Hogewoning et al., 2010; Massa et al., 2008).

4.2 Effects of red, blue, green, far-red, and UV spectra

Red light is one of the most photosynthetically efficient wavebands because it closely aligns with chlorophyll absorption maxima. Red-enriched spectra often increase dry matter accumulation and canopy expansion, making red photons central to many commercial lighting systems. However, red light supplied in isolation may reduce stomatal conductance and alter leaf anatomy, limiting long-term crop performance (Hogewoning et al., 2010; Massa et al., 2008). Blue light plays an essential role in photomorphogenesis, chlorophyll synthesis, stomatal regulation, and compact growth. Moderate blue fractions generally produce thicker leaves, improved pigmentation, and greater photosynthetic competence. Excessive blue light, however, may suppress extension growth and reduce leaf area in some species, demonstrating the need for balanced spectral formulations rather than simple maximization of blue photons (Hogewoning et al., 2010; Zheng et al., 2019).

Green light was historically considered less useful because leaves reflect much of it, but more recent evidence shows that green photons penetrate deeper into leaf tissues and dense canopies than red or blue wavelengths. Different wavelengths produce distinct physiological and morphological responses across crop species, as summarized in Table 2. This deeper penetration can enhance whole-canopy photosynthesis and improve light distribution in multilayer systems. Green wavelengths may also modify plant architecture and visual quality, which is relevant for marketable crops (Ptushenko et al., 2020). Far-red radiation strongly influences plant architecture through phytochrome signaling. Supplemental far-red can promote stem extension, leaf expansion, and flowering responses. In some crops, this increases canopy photon interception and biomass accumulation, although responses depend on species, developmental stage, and interactions with red and blue light fractions (Spaninks et al., 2020). Ultraviolet radiation, especially UV-A and carefully managed UV-B exposure, is often used to stimulate secondary metabolites such as flavonoids, anthocyanins, and antioxidants. These compounds are important for nutritional quality and stress resistance. Responses are highly dose-dependent, and excessive UV can reduce yield or damage tissues, making controlled application essential in commercial systems (Warner and Erwin, 2021).

TABLE 2 Effects of different LED spectra on crop performance.

LED spectrum	Main physiological role	Common crop responses	Main limitation or risk	Citations
Red light	Strongly supports photosynthesis because it closely matches chlorophyll absorption peaks	Often increases dry matter accumulation, canopy expansion, and biomass production	Red light alone may reduce stomatal conductance, impair morphology, and limit long-term physiological performance	Hogewoning et al. (2010); Massa et al. (2008)
Blue light	Regulates photomorphogenesis, chlorophyll synthesis, stomatal function, and compact growth	Commonly produces thicker leaves, improved pigmentation, greater photosynthetic competence, and more compact plant form	Excessive blue light may suppress extension growth and reduce leaf area in some species	Hogewoning et al. (2010); Zheng et al. (2019)
Green light	Penetrates deeper into leaf tissues and dense canopies than red or blue wavelengths	Can improve whole-canopy photosynthesis, light distribution, plant architecture, and visual quality	Historically undervalued; direct effects may be less obvious than red and blue when assessed at leaf level alone	Ptushenko et al. (2020)
Far-red light	Influences phytochrome signaling and plant architectural responses	Can promote stem extension, leaf expansion, flowering responses, greater canopy photon capture, and in some cases higher biomass	Responses are highly species-specific and may lead to undesirable elongation if poorly balanced with red and blue light	Spaninks et al. (2020)
UV radiation	Stimulates protective and secondary metabolic pathways, especially under controlled low-dose exposure	Can enhance flavonoids, anthocyanins, antioxidants, and other quality-related metabolites	Highly dose-dependent; excessive UV may reduce yield and damage plant tissues	Warner and Erwin (2021)

4.3 Crop-specific light recipes

The concept of crop-specific light recipes has become central to LED-based CEA because optimal spectral conditions vary across species and production objectives. Leafy vegetables such as lettuce commonly perform well under red-dominant spectra supplemented with moderate blue light. Such combinations often support rapid biomass accumulation while maintaining compact morphology and acceptable pigment content (Alrajhi et al., 2023; Mohamed et al., 2021). Herbs such as basil require more complex optimization because market value depends on aroma, essential oil composition, leaf texture, and appearance in addition to yield. Variations in red: blue ratios have been shown to influence biomass production, nutrient-use efficiency, and phytochemical profiles in basil, indicating that productive lighting strategies for herbs must integrate both quantitative and qualitative outcomes (Pennisi et al., 2019).

Fruiting crops such as tomato, pepper, and strawberry require stage-specific lighting strategies because vegetative growth, flowering, fruit set, and ripening respond differently to light environments. Research on strawberry has shown that spectral manipulation can alter flavonoid accumulation and fruit quality, while greenhouse studies on tomato indicate that supplemental spectra affect flowering and productivity. These findings show that light recipes should be dynamic rather than fixed throughout the crop cycle (Warner and Erwin, 2021; Zheng et al., 2019). No single spectrum is universally optimal. Effective light recipes must integrate wavelength composition, intensity, photoperiod, and developmental timing according to crop biology and market goals. This principle is especially relevant in urban CEA systems that cultivate multiple high-value crops simultaneously (Stamford et al., 2023).

4.4 Energy efficiency and economic implications of LEDs

The widespread adoption of LEDs in CEA has been accelerated by major improvements in electrical efficiency and fixture performance. Compared with high-pressure sodium and fluorescent systems, LEDs generally provide higher photosynthetic photon efficacy, lower radiant heat output, longer operational life, and greater controllability. These advantages are particularly valuable in multilayer indoor farms where heat management and precise light placement influence productivity and infrastructure costs (Morrow, 2008; U.S. Department of Energy, 2020). Lighting is often the largest single electricity demand in indoor agriculture. Economic viability therefore depends heavily on converting electrical energy into marketable biomass or quality attributes efficiently. LEDs can reduce power consumption relative to legacy systems, but profitability still depends on crop value, local electricity prices, fixture lifespan, and biological response to the chosen light strategy (Gómez et al., 2019; U.S. Department of Energy, 2020).

Capital costs for horticultural LED installations may exceed those of older lighting technologies, yet these costs can be offset when higher yields, improved quality, reduced cooling demand, and lower maintenance costs are achieved over time. Economic evaluation should therefore consider total system performance rather than purchase price alone. Recent literature increasingly emphasizes dynamic lighting, stage-specific spectra, and data-driven light scheduling as pathways to maximize both biological efficiency and economic return in commercial CEA operations (Stamford et al., 2023; Zheng et al., 2019).

5 Intelligent plant nutrient delivery systems

5.1 Hydroponic systems

Hydroponic systems are the most widely used nutrient delivery platforms in controlled environment agriculture because they allow direct control of water and mineral nutrition without reliance on soil. In these systems, plant roots are supplied with dissolved macro- and micronutrients in carefully prepared solutions, allowing rapid nutrient uptake, precise root-zone regulation, and high production efficiency. Their importance in controlled environment agriculture is closely linked to the need for intensive production under limited land availability, especially in urban settings where soil quality, contamination, and space constraints often restrict conventional cultivation (Fathidarehnijeh et al., 2024; Rajaseger et al., 2023).

Several hydroponic configurations are used in practice, including nutrient film technique, deep water culture, ebb-and-flow systems, drip irrigation systems, and substrate-based culture. Although these systems differ in engineering design, they share the same principle of supplying nutrients in soluble form under controlled conditions. Crop performance in hydroponics depends largely on nutrient solution formulation, irrigation frequency, dissolved oxygen availability, and the stability of physicochemical properties in the root zone. Efficient hydroponic management therefore requires a balance between nutrient supply, water availability, and aeration to sustain growth and quality over time (Fathidarehnijeh et al., 2024; Rajaseger et al., 2023). Hydroponics is also valued for its potential to improve nutrient use efficiency and water use efficiency compared with conventional soil-based cultivation. This advantage is especially important in urban agriculture, where sustainability and resource conservation are central concerns. Even so, system performance varies according to crop species, environmental conditions, and whether the nutrient solution is discharged after use or recirculated for reuse. These factors make nutrient management one of the most critical determinants of hydroponic success in controlled environment production (Fathidarehnijeh et al., 2024).

5.2 Aeroponic and aquaponic systems

Aeroponics is a soilless culture technique in which plant roots are suspended in air and intermittently misted with nutrient solution. This method enhances root-zone aeration and permits efficient delivery of water and dissolved nutrients directly to the root surface. Reviews of aeroponic production emphasize its suitability for high-value crops, propagation systems, and environments where water conservation is important. Faster nutrient absorption, improved oxygen availability, and lower water consumption are often cited as major strengths of the system (Garzón et al., 2023). Despite these advantages, aeroponic systems require careful technical management. Nozzle blockage, irregular misting, pump failure, and vulnerability to interruptions in power supply can quickly compromise plant performance because roots are not buffered by a water reservoir or solid substrate. Successful use of aeroponics therefore depends on reliable engineering design, regular maintenance, and close monitoring of nutrient delivery cycles (Garzón et al., 2023).

Aquaponics integrates hydroponic crop cultivation with aquaculture, using nutrient-rich water derived from fish production as a source of plant nutrition. This creates a circular production model in which dissolved nutrients from fish waste are absorbed by plants before water is returned to the fish unit. Aquaponics has been recognized as an attractive strategy for sustainable urban and peri-urban agriculture because it combines nutrient recycling, water reuse, and simultaneous production of plant and fish biomass (Ibrahim et al., 2023; Patloková et al., 2024).

Nutrient management in aquaponics is more complex than in conventional hydroponics because nutrient availability is determined not only by crop demand but also by fish metabolism, feed composition, microbial conversion, and system balance. Reviews have shown that nutrient deficiencies, especially of iron, potassium, calcium, and certain micronutrients, are common when fish effluent alone is expected to meet crop requirements. This means that aquaponics often requires supplementation and more sophisticated nutrient balancing if high plant productivity is to be maintained (Ibrahim et al., 2023; Patloková et al., 2024).

5.3 Precision fertigation and recirculating nutrient solutions

Precision fertigation refers to the controlled application of water and dissolved nutrients in quantities and timing that closely correspond to plant demand. In controlled environment agriculture, this approach has progressed from manual scheduling toward automated systems supported by sensors, controllers, and data-based management tools. Precision fertigation is particularly valuable in greenhouse and indoor systems because crop growth can be strongly affected by even small deviations in nutrient concentration, irrigation timing, or root-zone chemistry (Lin et al., 2020; Silva et al., 2024). Recirculating nutrient solutions form an important part of sustainable nutrient management in controlled environments. In closed-loop systems, unused nutrient solution is collected, corrected, and reused rather than discarded. This approach improves fertilizer and water efficiency, reduces environmental discharge, and supports more sustainable production. At the same time, solution recirculation increases the risk of nutrient imbalance, salt accumulation, and pathogen spread when monitoring is inadequate. Long-term reuse therefore requires careful adjustment of nutrient composition rather than simple replacement of water losses (Fathidarehnijeh et al., 2024).

Conventional fertigation control has often relied on bulk measurements such as electrical conductivity, but this approach does not fully capture changes in ionic composition over time. Two nutrient solutions may have similar EC values while differing substantially in the proportions of nitrate, potassium, calcium, magnesium, or other ions. For this reason, recent work in precision fertilization has emphasized ion-specific sensing, automated dosing systems, and real-time feedback technologies that improve nutrient-use efficiency and reduce unnecessary fertilizer application (Silva et al., 2024).

The shift toward intelligent nutrient delivery reflects a broader transition in controlled environment agriculture from fixed nutrient schedules to responsive management. Fertigation systems are increasingly designed to adjust nutrient supply according to plant developmental stage, transpiration, substrate moisture, and solution composition. This makes recirculating systems more productive and more sustainable, especially in urban production where efficiency is a major requirement (Lin et al., 2020; Silva et al., 2024).

The operational features and resource efficiencies of major nutrient delivery systems are compared in Table 3.

5.4 Monitoring and control of pH, EC, and nutrient composition

Monitoring and controlling pH and electrical conductivity are fundamental to hydroponic and fertigation management. Root-zone pH influences nutrient solubility, chemical stability, and ion uptake, while EC provides an estimate of the total concentration of dissolved salts in solution. These two parameters are used routinely because they offer rapid and practical indicators of whether the nutrient environment remains suitable for plant growth (Alexopoulos et al., 2021; Méndez-Cifuentes et al., 2023).

pH management is especially important because nutrient availability changes markedly outside the optimal range. Excessively low or high pH can reduce uptake of essential elements and may cause toxicity or deficiency symptoms even when nutrients are present in the solution. Experimental work in floating hydroponics showed that nutrient solution pH significantly affected the growth, yield, and quality of *Taraxacum officinale* and *Reichardia picroides*, with better performance recorded at pH 5.5 than at pH 4.0 (Alexopoulos et al., 2021). These findings illustrate the importance of maintaining a stable and crop-appropriate root-zone acidity level. Electrical conductivity is equally important because it reflects the overall strength of the nutrient solution. When EC is too low, nutrient supply may be insufficient to support vigorous growth; when it is too high, osmotic stress can limit water uptake and suppress yield. Research on sub-irrigated tomato production demonstrated that nutrient-solution EC significantly affected yield and growth, and that EC management needed to be adjusted over time to avoid salinity build-up and production losses (Méndez-Cifuentes et al., 2023). This indicates that fixed EC targets are often inadequate in long-cycle or recirculating systems.

Recent developments in intelligent nutrient management extend beyond pH and EC alone. Ion-selective sensors, automated dosing units, and digital control platforms are increasingly being explored to monitor nutrient composition more directly and to regulate fertilizer application with greater precision. This transition is important because EC does not distinguish among ions, and nutrient imbalances can develop even when EC remains within an acceptable range. More detailed monitoring therefore improves nutrient-use efficiency, reduces waste, and supports more stable crop performance in advanced controlled environment systems (Fathidarehnijeh et al., 2024; Silva et al., 2024).

TABLE 3 Comparison of intelligent nutrient delivery systems.

System	Core principle	Main strengths	Main limitations	Best-suited crops/use cases	Key citations
Hydroponics	Plant roots are supplied directly with dissolved nutrients in water or inert substrate under controlled conditions	Precise nutrient delivery, high nutrient-use efficiency, high water-use efficiency, strong suitability for urban CEA	Requires close control of nutrient formulation, irrigation frequency, dissolved oxygen, pH, and EC; performance varies with whether solution is open or recirculated	Leafy greens, herbs, seedlings, and many high-value horticultural crops	Fathidarehnijeh et al. (2024); Rajaseger et al. (2023)
Aeroponics	Roots are suspended in air and intermittently misted with nutrient solution	Excellent root-zone aeration, rapid nutrient absorption, lower water use, strong performance for high-value crops and propagation	Technically sensitive; nozzle blockage, pump failure, irregular misting, and power interruption can quickly damage crops	Propagation systems, herbs, leafy crops, and high-value specialty crops	Garzón et al. (2023)
Aquaponics	Integrates hydroponics with aquaculture by using fish-effluent water as a nutrient source for plants	Nutrient recycling, water reuse, circular production, simultaneous fish and plant output	Nutrient supply is harder to balance; common deficiencies include iron, potassium, calcium, and some micronutrients; often needs supplementation	Sustainable urban and peri-urban mixed production systems	Ibrahim et al. (2023); Patloková et al. (2024)
Precision fertigation	Applies water and dissolved nutrients in amounts and timing that closely match plant demand, often with sensors and automation	Improves nutrient-use efficiency, enables responsive management, supports crop-stage-based dosing, reduces waste	Requires monitoring infrastructure, control systems, and accurate feedback on root-zone chemistry and plant demand	Greenhouse crops, indoor systems, fruiting crops, and advanced commercial CEA	Lin et al. (2020); Silva et al. (2024)
Recirculating nutrient solutions	Unused nutrient solution is collected, corrected, and reused in closed-loop systems	Improves fertilizer and water efficiency, reduces environmental discharge, supports sustainability goals	Risk of nutrient imbalance, salt accumulation, and pathogen spread if monitoring is poor; long-term reuse needs careful compositional correction	Hydroponic and indoor urban production systems where input efficiency is a priority	Fathidarehnijeh et al. (2024); Lin et al. (2020); Silva et al. (2024)
pH-, EC-, and ion-guided nutrient control	Uses pH, EC, and increasingly ion-specific sensing to regulate nutrient composition more precisely	Better nutrient stability, improved nutrient-use efficiency, less waste, stronger crop consistency	EC alone cannot distinguish among ions; requires advanced sensors, dosing systems, and digital control tools	Advanced hydroponic, fertigation, and recirculating systems	Alexopoulos et al. (2021); Méndez-Cifuentes et al. (2023); Silva et al. (2024)

6 Interaction between LED lighting and nutrient systems

6.1 Light effects on nutrient uptake and assimilation

Light quality strongly influences nutrient uptake and assimilation because it regulates photosynthesis, stomatal behavior, transpiration, membrane transport, and the activity of enzymes involved in nitrogen metabolism. In controlled environment agriculture, these effects become more pronounced because light spectra can be manipulated independently of other environmental variables. Red and blue wavelengths are particularly important in this context (Arksey and O'Malley, 2005). Red light supports carbon assimilation and biomass formation, whereas blue light contributes to stomatal opening, chloroplast development, and nutrient transport processes. Reviews on spectral regulation have shown that blue light can alleviate the physiological limitations associated with monochromatic red light and improve nutrient accumulation and leaf functionality, especially in leafy vegetables and horticultural crops (Hogewoning et al., 2010; Trivellini et al., 2023b; Zheng et al., 2019).

Evidence from lettuce and basil studies further shows that spectral composition can modify plant nutritional status and resource-use efficiency. In lettuce, different LED combinations altered growth, mineral composition, and nutritional quality, indicating that light management affects nutrient acquisition and partitioning rather than growth alone. In basil, variation in red: blue ratios changed resource-use efficiency and nutritional properties, demonstrating that nutrient utilization responds to spectral balance in a crop-specific manner (Alrajhi et al., 2023; Pennisi et al., 2019). Light-driven nutrient assimilation is also closely associated with nitrogen metabolism. Changes in irradiance and spectral quality affect nitrate reductase activity, chlorophyll synthesis, amino acid formation, and carbon–nitrogen balance. Recent review literature on indoor vertical farming highlights that light intensity and duration can enhance nitrogen metabolism and biomass accumulation, while overly prolonged exposure may impair photosynthetic efficiency, indicating that nutrient assimilation depends on optimized light regimes rather than maximum light input alone (Gauthier and Marcelis, 2025; Wu et al., 2025).

6.2 Combined influence on photosynthesis and biomass accumulation

The interaction between LED lighting and nutrient systems is central to photosynthesis and biomass accumulation because shoot carbon gain and root nutrient supply are physiologically interdependent. Photosynthesis depends on sufficient mineral availability, especially nitrogen, magnesium, potassium, and iron, while nutrient uptake is driven in part by carbohydrate availability and transpiration generated by shoot activity. Controlled environment studies therefore show that growth responses are strongest when spectral design and nutrient delivery are optimized together rather than separately (Trivellini et al., 2023b; Sena et al., 2024). Blue light has been shown to increase photosynthetic competence, leaf thickness, and stomatal functionality, particularly when combined with red light. In cucumber, increasing blue-light fractions under red–blue LED combinations improved photosynthetic traits, morphology, and leaf chemical composition, confirming that spectral balance influences biomass formation through both physiological and structural pathways (Hogewoning et al., 2010).

Far-red radiation adds another layer to this interaction because it can modify canopy structure, light interception, and dry matter allocation. Recent work in vertical-farm lettuce showed that supplemental far-red increased harvestable biomass through morphological adjustments such as greater leaf expansion and improved canopy light capture. Such responses are important in nutrient-managed systems because increased leaf area can alter transpiration, nutrient flux, and whole-plant allocation patterns (Carotti et al., 2024). Nutrient concentration also shapes the efficiency with which plants convert light into biomass. Work under soilless controlled conditions has shown that nutrient concentration significantly affects shoot and root growth, yield, and chemical composition. This indicates that biomass gains attributed to optimized lighting cannot be interpreted fully without considering whether the nutrient regime is sufficient, excessive, or limiting. The most productive CEA systems therefore depend on coordination between spectral design and nutrient supply intensity (Abd Ghani et al., 2023).

6.3 Effects on plant quality and secondary metabolites

The interaction of light and nutrient availability also determines crop quality, especially the accumulation of pigments, antioxidants, vitamins, phenolics, glucosinolates, and other secondary metabolites. These compounds are particularly important in urban CEA because the commercial value of leafy greens, herbs, medicinal plants, and specialty vegetables often depends on nutritional and sensory quality as much as on yield. Review literature consistently shows that red and blue LEDs are major regulators of secondary metabolism, affecting anthocyanin synthesis, phenylpropanoid pathways, carotenoid accumulation, and antioxidant capacity (Trivellini et al., 2023b; Sena et al., 2024). Studies on basil, pak choi, and other leafy vegetables indicate that red–blue combinations often enhance nutritional quality, although the optimal ratio differs across species and production goals. In basil, changes in red:blue ratios altered nutritional properties together with resource-use efficiency. In red pak choi and other brassicas, LED treatments have been associated with higher anthocyanin, flavonoid, and phenolic accumulation, indicating that spectral engineering can be used to direct metabolite production under controlled cultivation (Drottberger et al., 2023a; Pennisi et al., 2019; da Cristina Bungala et al., 2024).

Nutrient supply interacts with these effects because secondary metabolite synthesis depends on carbon availability, mineral nutrition, and stress signaling. Nitrogen level, for example, can alter the balance between primary growth and phytochemical production, while spectral quality can modulate how these metabolic pathways are expressed. Recent indoor-fruiting-crop work showed that LED spectra and nitrogen levels interact to shape physiology, vegetative growth, fruit yield, and quality, reinforcing the view that metabolite outcomes are controlled jointly by aboveground and belowground management (Jibia et al., 2024).

6.4 Root–shoot responses under controlled environments

Root–shoot coordination provides the physiological basis for understanding how light and nutrient systems interact in CEA. Light signals perceived in the shoot can influence root development through photosynthate allocation, hormonal transport, and mobile signaling molecules. Conversely, root nutrient status can alter shoot architecture, leaf development, and assimilate partitioning. Reviews on root development and plasticity have shown that light affects root growth both indirectly, through carbohydrate supply from the shoot, and directly, through long-distance signaling involving hormones and other mobile factors (Heuvelink et al., 2025a; van Gelderen et al., 2018). Changes in spectral environment can therefore reshape biomass allocation between roots and shoots. Far-red perception in the shoot, for instance, has been shown to influence root architecture and biomass allocation, while nutrient limitation generally increases root investment relative to shoot growth as plants attempt to improve nutrient acquisition. Meta-analytic evidence indicates that nutrient deficiencies often increase root length per unit of shoot biomass, especially under nitrogen and phosphorus limitation, which highlights the sensitivity of root–shoot balance to resource supply (Lopez et al., 2023; Wang et al., 2025).

In controlled environments, these responses are especially relevant because both light and nutrient availability can be manipulated simultaneously. Root–shoot interactions determine whether changes in light spectrum enhance nutrient capture, whether nutrient supply supports the photosynthetic demand created by high irradiance, and whether biomass is directed toward edible tissues or structural growth. A mechanistic understanding of this coordination is essential for developing integrated light–nutrient strategies that maximize yield, quality, and resource-use efficiency across diverse crops in urban CEA systems (Trivellini et al., 2023b; van Gelderen et al., 2018). The interaction between light regulation and nutrient management determines crop growth, biomass accumulation, and quality outcomes, demonstrating the need for integrated optimization strategies in urban CEA (Figure 3).

7 Applications across diverse crop species

7.1 Leafy vegetables

Leafy vegetables remain the dominant crop category in controlled environment agriculture because they combine short production cycles, high market value, and strong responsiveness to controlled light and nutrient regimes. Lettuce is the most widely studied example and is frequently used as a model crop for evaluating LED spectra, nutrient solution management, and resource-use efficiency in indoor systems. Experimental evidence shows that spectral composition influences lettuce biomass, morphology, and nutritional composition, while hydroponic nutrient management further determines productivity and product quality. In red and green lettuce, LED treatments altered growth, yield, and nutritional traits, confirming that leafy vegetables respond strongly to integrated control of light and mineral nutrition (Levac et al., 2010; Alrajhi et al., 2023). Rocket, spinach, kale, and other leafy greens have also attracted increasing interest because they perform well under hydroponic and vertical-farming conditions. Their compact growth habit and rapid harvest cycle make them suitable for multilayer urban production systems. Recent work on lettuce and arugula in nutrient

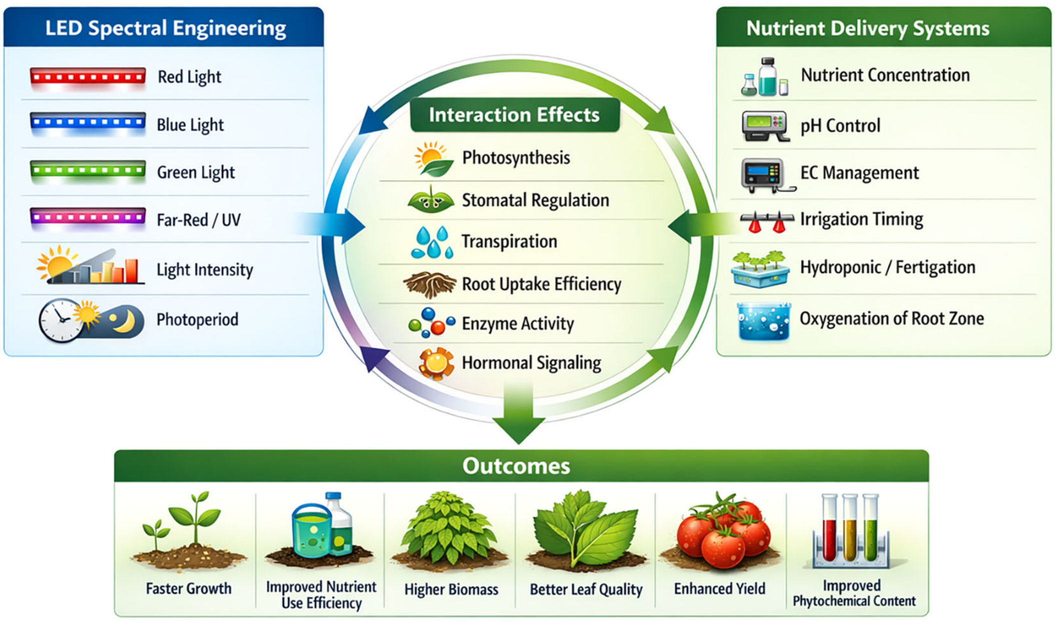

FIGURE 3
Interaction between LED spectral engineering and nutrient delivery systems.

film technique systems demonstrated that automated management can improve crop performance in container-based vertical farming, further illustrating the suitability of leafy vegetables for controlled urban production (Carrasco et al., 2024).

7.2 Herbs and medicinal plants

Herbs and medicinal plants represent an important application area for controlled environment agriculture because commercial quality depends not only on biomass production but also on aroma, color, essential oils, and bioactive compounds. Basil is one of the most intensively studied herb species in this context. Research has shown that red and blue LED combinations influence basil growth, resource-use efficiency, and nutritional properties, indicating that spectral engineering can be used to regulate both yield and quality traits simultaneously (Page et al., 2021; Pennisi et al., 2019). Further evidence from basil production under different lighting systems indicates that LED treatments can improve growth, physiological performance, and essential oil yield relative to conventional lighting. This is particularly relevant to medicinal and culinary herbs, where phytochemical composition often determines economic value. Reviews of basil production systems also show that light quality, photoperiod, pH, and nutrient management are closely interconnected in hydroponic cultivation, reinforcing the need for integrated environmental control in herb production (Aldarkazali et al., 2019; Rusu et al., 2021).

7.3 Fruiting crops

Fruiting crops such as tomato, pepper, cucumber, and strawberry present greater management complexity than leafy vegetables because their production cycle includes vegetative growth, flowering, fruit set, and ripening. These developmental stages often differ in their requirements for daily light integral, spectral composition, and nutrient supply (Snyder, 2019). As a result, fruiting crops require more dynamic production strategies in controlled environments than short-cycle leafy species. Recent work on tomato and bell pepper seedlings grown in indoor vertical farms demonstrated that both daily light integral and nutrient solution electrical conductivity significantly affected seedling quality, confirming that successful production depends on coordinated management of light and nutrient conditions (Adame-Adame et al., 2025).

Indoor strawberry production provides another clear example of this interaction. Experimental evidence has shown that LED spectrum and nitrogen level interact to shape plant physiology, vegetative growth, fruit yield, and fruit quality. Such findings highlight the importance of stage-specific lighting and nutrient strategies for fruiting crops, especially in enclosed systems where growers must optimize both energy use and crop value (Jibia et al., 2024). Reviews on LED applications in tomato cultivation similarly indicate that light quality affects growth, fruit development, and postharvest attributes, further confirming the sensitivity of fruiting species to controlled light environments (Arif et al., 2024).

7.4 Microgreens and specialty crops

Microgreens and specialty crops are increasingly important in urban controlled environment systems because they have short growth cycles, high market value, and strong nutritional appeal. Their rapid turnover makes them especially suitable for vertical farming and other compact systems where economic return depends on high output per unit area and frequent harvest. Research on Brassicaceae microgreens has shown that different red:blue LED ratios significantly affect growth and phytochemical traits, indicating that spectral design can be used to enhance both yield and functional quality in these crops (Brazaitytė et al., 2021). Interest in specialty crops has expanded beyond standard vegetable microgreens to include basil microgreens and other niche products targeted toward health-conscious and premium markets. Recent studies indicate that continuous blue lighting can increase antioxidant capacity, phenolic compounds, and vitamin C in basil microgreens, demonstrating that controlled lighting can be used strategically to produce value-added specialty crops with enhanced nutritional quality (Fayezizadeh et al., 2024). Reviews on microgreen production also emphasize that automation, controlled nutrition, and precise environmental regulation are becoming central to commercial-scale production of these crops (Ali et al., 2025; Malligarjunan, 2025).

7.5 Ornamental plants

Ornamental plants are another important application of controlled environment agriculture, particularly in floriculture and nursery production. In this crop group, quality traits such as plant architecture, flower induction, color development, compactness, and postharvest longevity are often more important than biomass alone. LED lighting has become increasingly valuable in ornamental production because spectral manipulation can regulate flowering, reduce excessive elongation, and improve visual quality while lowering dependence on chemical growth regulators and less efficient conventional lamps (Trivellini et al., 2023a). The relevance of controlled environments to ornamental crops extends beyond lighting alone. Nutrient management, photoperiod control, and environmental stability all contribute to the production of uniform, marketable plants. Recent review literature indicates that proper spectral selection in CEA can improve ornamental crop quality while also reducing energy and chemical inputs, which strengthens the role of LED-based systems in sustainable floriculture. This makes ornamental species a significant component of crop diversification in urban controlled environment agriculture, particularly where premium quality and year-round supply are essential (Tricco et al., 2018; Trivellini et al., 2023a).

8 Smart technologies and automation in urban controlled-environment agriculture

Smart technologies have become central to urban controlled-environment agriculture (CEA) because crop production in enclosed systems depends on precise regulation of temperature, humidity, light, carbon dioxide, irrigation, and nutrient delivery. In rooftop greenhouses, indoor farms, and plant factories, production outcomes are shaped less by external weather than by the quality of monitoring and control infrastructure. Scholarly reviews describe this shift as part of a broader transition from conventional greenhouse management to highly instrumented and automated production systems designed for urban conditions (Trivellini et al., 2023a; Shamshiri et al., 2018). Recent studies also show that digital monitoring, connected control systems, and predictive analytics are now closely tied to productivity, energy efficiency, and operational consistency in urban farming environments.

8.1 Sensor-based environmental monitoring

Sensor-based environmental monitoring provides the technical foundation for smart urban CEA. Effective monitoring systems usually track air temperature, relative humidity, carbon dioxide concentration, photosynthetic photon flux density, substrate moisture, pH, and electrical conductivity because these variables influence plant growth, nutrient uptake, and water use efficiency. Shamshiri et al. (2018) identify environmental perception and data sharing as core elements of advanced CEA, while Morella et al. (2023) explain that vertical farming systems require continuous measurement of key environmental and operational variables to support real-time management and economic evaluation. Continuous sensing is particularly important in urban systems because stacked layers and enclosed structures can create microclimatic variation within short distances, making periodic manual measurements insufficient for accurate control.

The significance of sensor networks extends beyond observation alone. High-frequency monitoring allows growers to detect rapid fluctuations in root-zone conditions, canopy temperature, humidity, and lighting before these disturbances reduce yield or quality. Reviews of IoT-enabled agriculture note that integrated sensing and data acquisition improve situational awareness and support timely interventions in precision crop production (Xiao and Watson, 2019; Alahmad et al., 2023). In urban CEA, sensor systems therefore function as an early-warning mechanism and as the data layer required for automated control of irrigation, nutrient dosing, ventilation, and lighting.

8.2 IoT and AI in nutrient and light management

IoT systems strengthen nutrient and light management by connecting distributed sensors, controllers, and actuators through shared data platforms. In nutrient management, this architecture supports continuous assessment of irrigation timing, nutrient solution pH, electrical conductivity, and water availability in the root zone. Sensor feedback allows fertigation to be adjusted in response to crop demand rather than fixed schedules, which is especially valuable in hydroponic and soilless systems where imbalances can affect growth quickly. Earlier decision-support research on fertigation in protected cultivation emphasized the need to connect substrate behavior, crop water demand, and nutrient supply within a structured management framework (Sánchez-Molina et al., 2015). That logic remains highly relevant in urban CEA, where even small deviations in nutrient concentration or irrigation frequency can lead to substantial inefficiencies. Light management has also advanced through connected sensing and intelligent control. LED-based systems are widely used in urban CEA because they allow regulation of spectrum, intensity, and photoperiod while generating less radiant heat than many conventional lighting systems. Pereira and Gomes (2025) report that sensor-guided LED control in vertical urban farming can automatically adjust artificial lighting according to natural light conditions and daily light integral targets, improving coordination between crop productivity and electricity use. This approach is important in urban agriculture because lighting is often one of the largest operating costs, especially in vertical farms and enclosed growing facilities. Sensor-informed light control therefore supports both biological efficiency and economic sustainability.

Artificial intelligence is increasingly used alongside IoT to improve climate and resource management. Lee et al. (2024) developed an AI-powered environmental control system that integrates weather forecasts, greenhouse microclimate forecasts, crop physiological indicators, and automated operational responses. Such systems move management beyond reactive correction by anticipating likely environmental changes and adjusting control actions in advance. In urban CEA, this predictive capacity is useful where energy constraints, tight production schedules, and quality standards require accurate coordination of cooling, dehumidification, irrigation, and lighting.

8.3 Predictive models and decision support systems

Predictive models and decision support systems help translate sensor data into actionable management decisions. Rather than treating environmental variables separately, these systems estimate how interacting factors influence crop growth, yield, quality, and resource use. Sánchez-Molina et al. (2015) showed that model-based support tools could guide greenhouse environmental management by linking crop responses to control variables. This principle is highly relevant in urban CEA, where management decisions often involve trade-offs among energy consumption, plant performance, labor use, and market timing. Decision support becomes most useful when it combines biological prediction with operational and economic considerations. Recent literature also shows growing interest in machine learning and deep learning for controlled-environment applications. Ojo and Zahid (2022) found that deep learning in CEA has been applied to crop monitoring, stress detection, irrigation management, yield prediction, and disease identification. These capabilities are important in urban agriculture because large volumes of image data, sensor streams, and operational records are generated each day. Predictive analytics can detect abnormal crop conditions earlier than manual inspection and can improve planning for irrigation, climate control, harvest timing, and input use. The result is a management system that is more adaptive, more precise, and less dependent on delayed human response.

Decision support systems are most effective when they do more than display raw data. A useful platform connects measurements with thresholds, forecasts, and management logic so that growers receive clear recommendations rather than isolated numbers.

Nutrient management becomes more effective when pH and electrical conductivity are interpreted alongside crop stage and irrigation history. Light management becomes more effective when daily light integral deficits are considered together with electricity demand and production targets. The literature on smart greenhouse and urban farming systems increasingly supports this integrated model of data interpretation and operational guidance (Lee et al., 2024; Shamshiri et al., 2018).

8.4 Automation for precision urban agriculture

Automation allows urban CEA systems to respond quickly and consistently to environmental changes. Pumps, valves, nutrient dosing units, fans, LED fixtures, dehumidifiers, and ventilation systems can now operate automatically based on sensor feedback or predictive control rules. Shamshiri et al. (2018) describe automation as a defining feature of the transition toward plant factories and urban agriculture because enclosed production systems depend on coordinated control of many variables at once. Precision in this context means that environmental adjustments are applied at the right time, in the right amount, and with minimal delay. This level of control is especially important in urban farming, where high land costs, limited space, and premium product expectations place pressure on productivity and consistency. Automation also reduces the cumulative effects of small management errors. Excess irrigation may reduce oxygen availability in the root zone, slight pH drift may limit nutrient uptake, and poorly timed lighting may raise energy costs without improving biomass production. Automated control systems reduce such errors by standardizing responses to measured conditions. Morella et al. (2023) note, however, that monitoring and automation infrastructure must also be evaluated economically because installation and operating costs influence the long-term viability of vertical farming systems. Precision urban agriculture therefore depends not simply on adding more technology, but on selecting control tools that improve crop performance, labor efficiency, and input use without creating unnecessary system complexity.

Overall, smart technologies and automation are reshaping urban CEA into a data-intensive production model built on sensing, connectivity, prediction, and machine-assisted control. Sensor networks provide continuous environmental visibility, IoT systems connect measurement with actuation, predictive models improve planning, and automation delivers timely operational responses. Current scholarship suggests that the competitiveness of urban CEA will depend not on isolated technologies, but on how effectively these tools are integrated into coherent management systems that improve yield stability, resource efficiency, and economic performance (Shamshiri et al., 2018; Ojo and Zahid, 2022; Lee et al., 2024).

9 Sustainability and economic perspectives

9.1 Resource use efficiency

Controlled environment agriculture (CEA) is widely promoted for its potential to improve resource-use efficiency, especially in urban areas where land is limited and climatic instability reduces the reliability of open-field farming. One of the most frequently cited advantages of CEA is its high land productivity. Vertical farming and other indoor systems make it possible to cultivate crops in stacked layers throughout the year, which can generate significantly higher yields per unit of land area than conventional field-based systems, particularly for leafy vegetables and herbs (Pennisi et al., 2025). This spatial efficiency explains why CEA is often considered a promising strategy for food production in densely populated cities. Resource efficiency in CEA, however, should not be treated as uniformly superior across all categories. Goldstein et al. (2016) observed that urban agriculture systems do not share a single resource profile, since performance varies depending on production technology, management intensity, and scale. More recent assessments support this view, showing that while CEA performs strongly in terms of land-use efficiency, it may perform less favorably in energy demand, material use, and labor requirements when compared with conventional agricultural systems (Pennisi et al., 2025). For this reason, sustainability assessments should distinguish clearly among land productivity, water-use efficiency, nutrient-use efficiency, and energy consumption rather than presenting resource efficiency as a single outcome.

Hydroponic and other soilless systems also contribute to efficient resource management because they allow tighter control over water and nutrient delivery. Regmi et al. (2024) reported that hydroponic systems can reduce water use by more than 90% and fertilizer use by approximately 60% compared with conventional systems, depending on crop type and system design. These improvements are linked to recirculation, reduced leaching, and targeted nutrient delivery to the root zone. Even so, the extent of these advantages differs across production settings, which means that claims regarding CEA efficiency should remain conditional and evidence-based rather than universal.

9.2 Water and nutrient conservation

Water conservation is one of the clearest environmental advantages associated with CEA. In hydroponic, aeroponic, and recirculating cultivation systems, water not absorbed by plants can be recovered, treated, and reused. This process substantially reduces losses from runoff, drainage, and evaporation when compared with many soil-based systems. Regmi et al. (2024) found that hydroponic and aquaponic systems generally recorded much lower daily water use than conventional soil cultivation while also achieving higher water-use efficiency. These findings align with broader reviews that identify water savings as one of the most consistent sustainability benefits of soilless urban food production systems (Pennisi et al., 2025). Nutrient conservation is closely connected to water management because recirculating systems can also minimize fertilizer losses to the surrounding environment. Closed-loop hydroponics, nutrient film technique, and sensor-guided fertigation systems can improve nutrient-use efficiency by limiting nutrient discharge and delivering dissolved fertilizers more precisely to plant roots. Current scholarship nevertheless emphasizes that recirculation only remains effective when nutrient solutions are monitored carefully. Imbalances in pH, electrical conductivity, and ionic composition can reduce nutrient availability, cause salt accumulation, and increase the risk of disease if solution management is neglected (Pennisi et al., 2025).

The conservation benefits of CEA therefore depend heavily on integration between water management, nutrient monitoring, and precision dosing. This issue is particularly important in urban agriculture, where the environmental legitimacy of intensive production systems depends partly on their ability to reduce waste streams and avoid nutrient pollution. Dsouza et al. (2023) noted that although technical research in CEA has expanded rapidly, especially in crop and lighting management, socio-environmental evaluation remains less developed. More standardized reporting of nutrient recovery, fertilizer-use efficiency, and discharge losses is therefore needed to strengthen sustainability comparisons across CEA systems.

9.3 Energy demand and environmental sustainability

Energy demand remains the most serious environmental limitation of indoor CEA, particularly in fully enclosed vertical farms that rely on electric lighting, cooling, dehumidification, and mechanical air circulation. Reviews of the field consistently identify lighting and climate control as the dominant sources of energy consumption in these systems (Aborujilah et al., 2025; Pennisi et al., 2025). As a result, the environmental performance of indoor farms depends strongly on the electricity source, lighting efficiency, insulation quality, and climate-control strategy adopted within the facility. Environmental sustainability in CEA is therefore highly context-specific rather than automatically guaranteed. Sohn et al. (2026) argued that vertical farming offers important benefits in land-use efficiency, water conservation, and resilience to climate variability, but these advantages are often accompanied by trade-offs involving energy demand, material inputs, and overall economic feasibility. Similar conclusions were drawn by Goldstein et al. (2016), who noted that the environmental value of urban agriculture depends on how systems are designed, where they are located, and whether they make use of otherwise underutilized urban spaces. CEA systems become more environmentally credible when they are supported by renewable electricity, efficient LED technologies, waste-heat recovery, and circular water and nutrient strategies.

Recent systematic reviews reinforce this conclusion. Aborujilah et al. (2025) emphasized that sustainability in vertical farming improves when farms combine energy-efficient lighting, optimized HVAC systems, renewable energy integration, and carbon-reduction strategies. High productivity alone does not ensure environmental sustainability when it is achieved through carbon-intensive power and resource-heavy infrastructure. Consequently, energy optimization and life-cycle assessment have become central themes in current CEA research and commercial planning.

9.4 Economic feasibility and commercial prospects

Economic feasibility remains one of the most debated issues in CEA. The commercial viability of these systems depends on whether the benefits of year-round production, consistent quality, and local supply can offset high capital costs, electricity expenses, labor requirements, and technology maintenance. Current evidence suggests that the strongest commercial prospects are concentrated in high-value, short-cycle crops such as lettuce, herbs, and microgreens, since these crops mature quickly, command premium prices, and are well suited to intensive indoor production systems (Pennisi et al., 2025). Cost structure plays a decisive role in indoor vertical farming. Lahlou et al. (2025) found in an economic comparison of greenhouse and vertical farm production in Qatar that vertical farms had a higher levelized production cost than greenhouse systems, with electricity prices exerting a particularly strong influence on the final cost per kilogram of produce. This finding does not indicate that vertical farming is inherently uneconomic, but it does show that profitability is highly sensitive to local conditions such as climate, energy costs, logistics, and market prices. Economic viability should therefore be understood as location-specific rather than universal.

Supply-chain optimization and production planning also affect the financial performance of CEA systems. Li et al. (2025) argued that profitability improves when crop selection, logistics, and operational planning are coordinated strategically. Vertical farms may gain a competitive advantage in places where transport costs are high, where greenhouse expansion is constrained, or where consumers are willing to pay a premium for freshness, local identity, and reliable quality. Even so, the literature also shows that commercial expansion remains limited by high initial investment, difficulty accessing finance, and the managerial complexity associated with technologically intensive production systems (Dietze et al., 2024; Dayananda et al., 2023). A balanced reading of the literature suggests that CEA has genuine commercial potential, but not as a universal substitute for conventional agriculture. Its strongest prospects appear in specialized market niches where local production, product quality, year-round availability, and resource efficiency justify the added financial and technological burden. Future economic performance will likely depend on lower lighting and climate-control costs, wider adoption of renewable energy, improved automation, and more rigorous benchmarking of cost, yield, and environmental performance across production systems (Aborujilah et al., 2025; Li et al., 2025).

10 Challenges, research gaps, and future directions

Urban controlled-environment agriculture (CEA) continues to attract interest because it offers year-round production, closer proximity to consumers, and greater control over crop conditions. At the same time, the literature shows that large-scale adoption remains constrained by technical complexity, high operating costs, narrow crop portfolios, and uneven policy support. A recent scoping review of 610 studies found that CEA research has concentrated heavily on biological and technical themes, especially plant-light interactions, while socio-economic and broader food-system questions remain underexamined (Dsouza et al., 2023). This imbalance suggests that the next phase of research must move beyond proving technical feasibility and address the conditions under which urban CEA can become economically durable, environmentally credible, and socially relevant.

10.1 Technical and operational constraints

Technical and operational constraints remain among the most persistent barriers to urban CEA. Energy demand is one of the most widely discussed limitations, especially in indoor vertical farms that depend on artificial lighting and climate control. Engler and Krarti (2021) note that many CEA systems involve energy-intensive processes, even though energy-efficiency measures in lighting, HVAC, dehumidification, and control systems can substantially reduce consumption. Their review also emphasizes that high operating costs remain a major obstacle to profitability, and that limited peer-reviewed energy-performance data still restricts evidence-based system design.

Recent benchmarking research confirms that energy remains a central challenge. Miserocchi and Franco (2025) report that current vertical farming systems for lettuce commonly operate within a specific energy consumption range of about 10–18 kWh per kilogram of product, while projected technical improvements could reduce this benchmark considerably. Even with those gains, the study concludes that electricity-related costs and environmental burdens remain significant barriers to short-term energy sustainability (Miserocchi and Franco, 2025). This finding is important for urban CEA because technical success alone does not guarantee commercial viability when production depends on expensive and energy-intensive infrastructure.

Operational complexity creates further constraints. Environmental control in urban CEA requires continuous coordination of light, temperature, humidity, carbon dioxide, irrigation, and nutrient supply. Small errors in one subsystem can rapidly affect crop performance, particularly in tightly coupled hydroponic or multilayer systems. Dohlman et al. (2024) observe that the expansion of CEA has been driven by technological progress, but they also note that economic, technical, and operational challenges continue to shape the sector's growth trajectory. Urban CEA therefore faces a dual burden: it must maintain biological precision while keeping labor, maintenance, and utility costs within commercially realistic limits.

10.2 Knowledge gaps in multi-crop optimization

A major research gap in urban CEA concerns multi-crop optimization. Much of the literature has focused on a narrow set of species, particularly leafy greens. Dsouza et al. (2023) found that leafy vegetables dominate the evidence base, with lettuce receiving the greatest research attention, followed by a much smaller number of studies on crops such as basil and tomato. The same review argues that increasing crop diversity is necessary if CEA is to contribute more meaningfully to food security and broader dietary needs.

This narrow crop focus creates several knowledge gaps. Environmental recipes developed for one crop often cannot be transferred directly to another because species differ in canopy

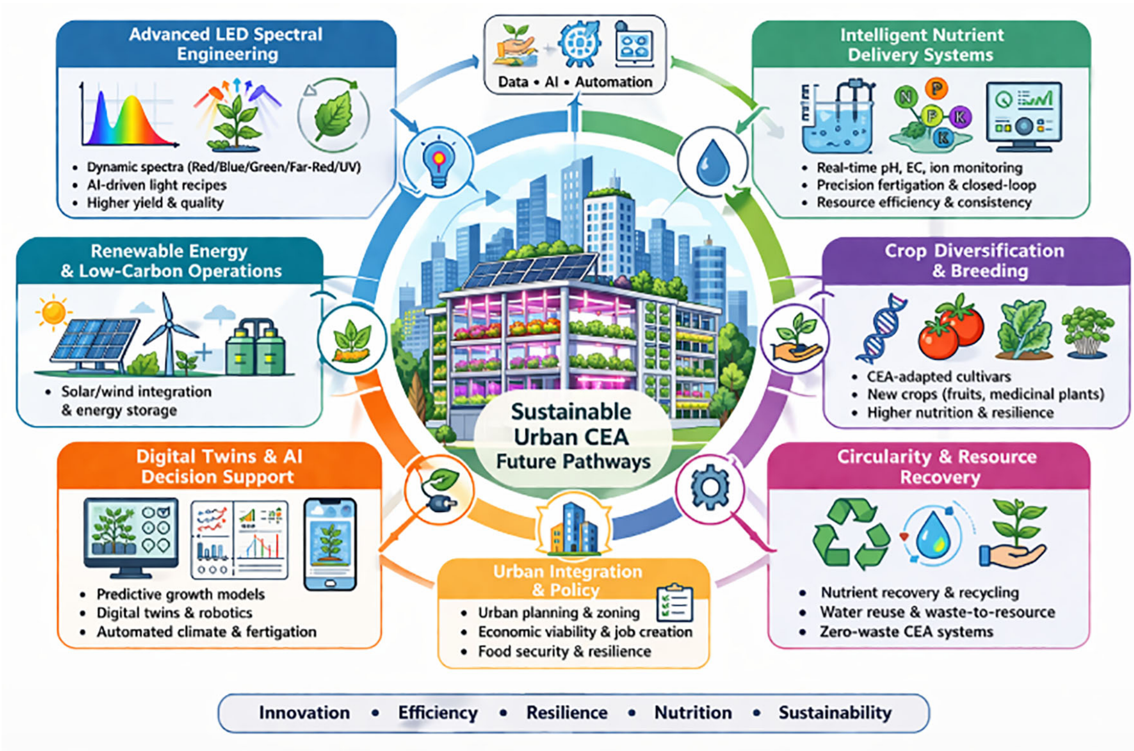

FIGURE 4
Future pathways for sustainable urban CEA.

structure, nutrient uptake, photoperiod sensitivity, growth rate, harvest index, and tolerance to temperature or humidity fluctuations. Multi-crop production therefore requires more than adding new species to existing systems; it requires crop-specific and system-specific optimization models that account for trade-offs among yield, quality, energy use, and space efficiency. Bhattarai et al. (2025) argue that many CEA producers still depend on cultivars bred for open-field conditions rather than varieties specifically adapted to indoor or protected systems. The review further notes that only a limited number of food crops have so far proven profitable in CEA, partly because breeding programs and trait selection have not yet kept pace with the needs of controlled environments.

The literature therefore points to a broader genetic and agronomic gap. CEA-specific breeding targets such as compact architecture, rapid growth, high edible biomass, nutrient-use efficiency, low energy demand per unit yield, and tolerance to dense planting remain underdeveloped for many crops (Bhattarai et al., 2025). Research on multi-crop optimization must also address scheduling, root-zone compatibility, differential lighting requirements, and economic trade-offs across crop combinations. Without that knowledge, urban CEA is likely to remain concentrated in a limited number of premium crops rather than evolving into a more diversified production system.

10.3 Policy, regulation, and scale-up challenges

Policy and regulatory conditions strongly influence whether urban CEA can scale beyond pilot projects and niche markets. Dietze et al. (2024), in a comparative study of London, Nairobi, and Singapore, show that urban CEA develops more readily where public institutions provide policy alignment, funding, training support, and a stable infrastructure base. Their analysis also shows that fragmented policy frameworks, competing urban priorities, and weak institutional support can significantly slow

TABLE 4 Major challenges and future research priorities in urban controlled-environment agriculture (CEA).

Challenge area	Current limitation	Research gap	Future research priority	Citations
Energy demand and efficiency	Indoor vertical farms depend heavily on artificial lighting, HVAC, dehumidification, and air circulation, which increases operating cost and environmental burden	Limited peer-reviewed benchmarking data across crops, facilities, and climatic regions; insufficient integration of energy, yield, and carbon metrics	Develop integrated performance frameworks that evaluate energy use, yield, quality, carbon intensity, and profitability together; improve lighting and climate-control optimization	Engler and Krarti (2021); Miserocchi and Franco (2025)
Technical and operational complexity	Urban CEA requires continuous coordination of light, temperature, humidity, carbon dioxide, irrigation, and nutrients; small errors can rapidly reduce crop performance	Limited evidence on long-term operational reliability, maintenance burdens, and labor-management trade-offs in commercial systems	Expand studies on automation reliability, maintenance strategies, labor efficiency, and cost-effective system integration	Dohlman et al. (2024); Shamshiri et al. (2018)
Narrow crop diversity	Most CEA research and commercial practice remain concentrated on lettuce and a small number of leafy greens, herbs, and premium crops	Weak evidence base for multi-crop production, crop scheduling, species compatibility, and crop-specific environmental recipes	Increase research on diversified crop portfolios, multi-crop optimization, and species-specific light–nutrient strategies	Dsouza et al. (2023); Bhattarai et al. (2025)
Cultivar limitations and breeding gaps	Many CEA systems still rely on cultivars bred for open-field conditions rather than indoor or protected systems	Limited breeding for compact architecture, rapid growth, high edible biomass, nutrient-use efficiency, and low energy demand per unit yield	Develop CEA-specific breeding programs targeting indoor adaptability, dense planting tolerance, and quality traits	Bhattarai et al. (2025)
Economic feasibility	High capital cost, electricity expense, technology maintenance, and financing constraints continue to limit commercial scalability	Insufficient comparative cost benchmarking across business models, cities, crops, and technology types	Conduct robust techno-economic analyses, cost benchmarking, and location-specific viability studies	Dohlman et al. (2024); Miserocchi and Franco (2025); Dietze et al. (2024)
Policy and regulatory barriers	Urban land competition, building regulations, utility pricing, food safety rules, and limited institutional support can slow adoption	Limited comparative evidence on how policy environments shape CEA success across cities and regions	Develop context-specific policy frameworks, urban planning support, and regulatory pathways suited to local food-system goals	Dietze et al. (2024)
Socio-economic and food-system integration	Research remains heavily weighted toward technical and biological themes, with less attention to labor, markets, consumers, and food-system roles	Weak understanding of how urban CEA contributes to resilience, food security, market access, and social outcomes under different urban conditions	Expand interdisciplinary research on labor, consumer acceptance, market access, governance, and city-level food-system integration	Dsouza et al. (2023); Dohlman et al. (2024)
Environmental assessment and sustainability trade-offs	Land and water efficiencies may be offset by high energy use and material demand	Limited standardized reporting of life-cycle impacts, nutrient recovery, and integrated sustainability indicators	Strengthen life-cycle assessment, circular resource accounting, and comparative environmental evaluation across systems	Engler and Krarti (2021); Dsouza et al. (2023)

implementation. In Singapore, public backing has supported CEA as part of food-resilience strategy, whereas in London and Nairobi misalignment between urban conditions and policy support has constrained expansion (Dietze et al., 2024). Scale-up challenges are not only technical or financial; they are also institutional. Urban land competition, building regulations, utility pricing, food safety rules, and labor requirements can all affect the feasibility of commercial CEA. Dietze et al. (2024) further argue that public support should not be treated as a generic solution, because the rationale for subsidizing or promoting CEA depends on local goals such as resilience, import substitution, environmental performance, or urban regeneration. This suggests that policy frameworks must be context-specific rather than based on universal assumptions that urban CEA is automatically desirable or economically appropriate in every city.

The question of scale is especially important in lower-income or infrastructure-constrained settings. Dietze et al. (2024) conclude that CEA is more likely to succeed in locations with strong capital availability, specialized knowledge, stable political and infrastructural conditions, and limited space for conventional agriculture. That conclusion tempers overly optimistic claims about universal scalability and points toward a more selective understanding of where urban CEA is likely to deliver sustained value.

10.4 Future research priorities

Future research on urban CEA needs to become more interdisciplinary and more comparative. Dsouza et al. (2023) explicitly call for broader work on socio-economic, environmental, and food-security dimensions, noting that current scholarship still gives insufficient attention to these areas. Research priorities should therefore include robust cost analyses, labor studies, market access, consumer acceptance, and realistic assessments of how urban CEA contributes to local food systems under different urban conditions. Environmental assessment also requires stronger methodological attention. Engler and Krarti (2021) highlight the need for further work on controls, dehumidification, lighting, and crop variety in order to improve the sustainability and wider adoption of CEA. At the same time, Miserocchi and Franco (2025) show that energy sustainability depends on trade-offs rather than simple efficiency claims. Future research should therefore move toward integrated performance frameworks that evaluate yield, quality, energy demand, carbon intensity, water use, and profitability together rather than in isolation.

Crop development and breeding should also become a major research priority. Bhattarai et al. (2025) make clear that the continued use of open-field cultivars limits the potential of CEA systems. Developing cultivars specifically adapted to multilayer, low-volume, or highly managed environments could improve productivity and reduce resource costs across a wider crop range. This direction is essential if urban CEA is to move beyond lettuce-centered production and support diversified horticultural supply chains. Finally, future work should investigate how urban CEA fits into broader food-system planning. Dohlman et al. (2024) document the growth of CEA and the increasing policy and investment interest surrounding it, but they also underline that growth opportunities come with substantial economic and technical challenges. Research that compares cities, business models, governance structures, and infrastructure systems will be necessary to determine where urban CEA can complement rather than simply imitate conventional agriculture. The strongest future direction is not the pursuit of scale at any cost, but the identification of production models that are technically sound, economically resilient, environmentally defensible, and socially justified. Future progress in urban CEA will depend on coordinated advances in energy systems, crop breeding, automation, policy support, and economic scalability (Figure 4). Key barriers to large-scale adoption and corresponding research priorities are presented in Table 4.

Conclusion

Urban controlled-environment agriculture represents an important shift in modern food production because it combines biological precision with digital control, resource management, and year-round cultivation. The reviewed literature indicates that advances in sensing, automation, and decision-support systems have significantly strengthened the technical capacity of urban CEA, while hydroponic and closed-loop systems have improved land and water productivity. At the same time, high energy requirements, financial constraints, narrow crop diversity, and policy fragmentation continue to limit broader adoption and commercial scalability. The strongest future pathway for urban CEA lies not in presenting it as a universal replacement for conventional agriculture, but in positioning it as a specialized and strategic complement within urban food systems. Greater progress will depend on energy optimization, crop diversification, CEA-specific breeding, stronger regulatory support, and integrated research that evaluates environmental, economic, and operational performance together. In this sense, the long-term relevance of urban CEA will be determined less by technological novelty alone than by its capacity to deliver efficient, scalable, and context-responsive food production.

Author contributions

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