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Finding sustainable, resilient, and scalable solutions for future indoor agriculture

Liping Wang[1,2] ✉, Leslie Norford[3] ✉, Adam Arkin[4,5] ✉, Genhua Niu[6], Simone Valle de Souza[7], Azlan Zahid[6], Patrick M. Shih[8,9], Mary Ann Piette[10] & Baskar Ganapathysubramanian[11]

Controlled environment agriculture (CEA) enhances food resilience. However, CEA faces major challenges—high energy intensity and carbon footprints. Technological advancements are essential to reduce operational costs and promote CEA sustainability. This perspective article explores key technological innovations poised to enhance CEA sustainability, emphasizing the necessity of transdisciplinary approaches. We examine integrated decision-making frameworks informed by comprehensive life cycle analysis, distributed indoor agriculture, electricity demand flexibility, Digital Twins, and engineered microbiomes and plants optimized for CEA systems. For each area, we assess the current state of research, identify knowledge gaps, and outline future directions. For example, comprehensive life cycle analysis incorporates environmental, economic and social dimensions can inform both CEA decision making and community-scale circular economy planning; grid-integrated control strategies can enable CEA facilities to provide ancillary grid services, improving both economic viability and grid resilience. A holistic transdisciplinary approach is essential to drive a sustainable future for the CEA sector.

Overview

Traditional open-field agriculture production and food distribution are increasingly impacted by changing climate[1], driven by such factors as arable land degradation, groundwater depletion, and extreme weather events. The Food and Agriculture Organization (FAO)[2] reports a global loss of 75 billion tons of soil from arable land each year due to soil erosion, nutrient leaching, spreading of soil contaminants, and desertification. In the United States (U.S.), 4.7 tons of topsoil are washed from every hectare of cropland per year, with a predicted increase of soil erosion from 8% to 21% by 2050[3]. Major aquifers supplying 90% of water systems in the U.S. are rapidly being depleted, inflicting further harm on open-field agriculture[4]. Moreover, as natural disasters become more frequent, the food supply chain becomes even more vulnerable[5,6]. Globally, nearly one-third of food is wasted from farm to fork annually[7–10]. In the U.S., the retail industry, food services, and households generated 66.2 million tons of food waste in 2019[11], exacerbating food and nutrition insecurity challenges. We are seeking a new solution to boost crop productivity on limited arable land and ensure the resilience of food and nutrition security in the face of climate change while reducing food waste across agricultural production and food distribution.

Controlled environment agriculture (CEA) enhances food resilience through diversified sources, high productivity, water conservation, and protection against climate uncertainties, while promoting equitable food access for all communities. In CEA, crops grow under controlled conditions that include light (spectrum and intensity), temperature, and humidity. Crop yields (tons/hectare/year) in CEA are reported to range between 10 and 100 times higher than open-field agriculture[12–14]. Water use in CEA is typically about 4.5–16% of that from conventional farms per unit mass of produce[15,16]. CEA benefits communities by providing diversified food sources and the ability to shield food production from the uncertainties of climate conditions. CEA permits year-round crop growth with consistent

[1]Department of Civil and Architectural Engineering, University of Wyoming, Laramie, WY, USA. [2]Center for Controlled Environment Agriculture, University of Wyoming, Laramie, WY, USA. [3]Department of Architecture, Massachusetts Institute of Technology, Cambridge, MA, USA. [4]Environmental Genomics and Systems Biology, Lawrence Berkeley National Laboratory, Berkeley, CA, USA. [5]Department of Bioengineering, University of California, Berkeley, CA, USA. [6]Texas A&M AgriLife Research and Extension Center, Texas A&M University System, Dallas, TX, USA. [7]Department of Horticulture, Michigan State University, East Lansing, MI, USA. [8]Department of Plant and Microbial Biology, University of California, Berkeley, CA, USA. [9]Joint BioEnergy Institute, Lawrence Berkeley National Lab, Emeryville, CA, USA. [10]Energy Technologies Area, Lawrence Berkeley National Laboratory, Berkeley, CA, USA. [11]Department of Mechanical Engineering, Iowa State University, Ames, Iowa, USA. ✉e-mail: lwang12@uwyo.edu; lnorford@mit.edu; aparkin@lbl.gov

quality and predictable output, shortens food miles), and provides social and health benefits to communities. This perspective article focuses on plant-based CEA production, rather than emerging novel food systems (e.g. cellular agriculture and microbial food[17–19]).

CEA is experiencing swift global growth, with each country tailoring it to meet its specific challenges. In China, CEA is driven by rising food demand, the need for pesticide-free produce, an aging agricultural workforce, heat stress, and food insecurity from natural disasters. Government policies support innovation in indoor agriculture and rural revitalization[20]. Singapore aims to meet 30% of its nutritional needs by 2030 through advanced CEA technology to enhance food production and security[21]. Canada's vertical farming industry is driven by consumer preferences, environmental sustainability, and technological advancements, supported by government policies and research funding[22]. For developing countries such as Kenya, Nigeria, India, and Sri Lanka, CEA contributes to food security, safety and quality while promoting social equity and providing job opportunities[23].

While fast-growing, CEA remains relatively immature as an industry, with many indoor farming companies having failed due to challenges in technology adoption, business model viability, and operational scalability[24,25]. CEA grapples with issues ranging from design and operation to workforce development. The energy-intensive nature and high carbon footprints of the industry[26,27] make it difficult for CEA, especially vertical indoor farming, to be sustainable. Energy associated with artificial lighting, temperature control, and ventilation accounts for about 25% of the operating costs of large vertical farms in the United States. Energy is the second largest overhead cost in CEA, exceeded only by labor[28–30]. Carbon footprints were reported as 5.6–16.7 times and 2.3–3.3 times greater than that of open-field agriculture for indoor vertical farms and greenhouses, respectively[31]. Therefore, emerging technologies and advancements in fundamental science are essential for CEA to achieve significant resource efficiency[32] and reduce operational costs while maximizing productivity[33].

Current CEA technologies

Greenhouses and indoor vertical farms are among the most prominent CEA types, with greenhouses currently dominating the market[34]. Other systems—such as shipping container farms and hydroponic systems integrated in the built environment—also play an important role in CEA development and adoption. Greenhouses employ translucent structures that harness solar light, with energy-efficient light-emitting diode (LED) lighting as a supplement to support growth. However, external weather conditions can lead to high energy costs[35,36]. Indoor vertical farms, where crops grow hydroponically in stacked structures, are hermetically sealed and therefore require exclusive use of sole-sourced lighting systems. LED technology has empowered researchers to manipulate the specific spectrum and light intensity for crops; however, the significant capital investment and ongoing electricity costs—particularly at large scales—remain key challenges to economic viability. Over the past decade, there has been a surge in reported research investigating the effects of light environment and other key environmental conditions such as temperature and CO_2 concentration, on crop yield, morphology, and nutritional quality[37–39].

Nutritional quality of plant products is affected by the growing conditions such as temperature, light, and fertility management and measured by the concentrations of specific mineral elements and compounds like phenolics, vitamins, and antioxidants. Light was one of the main factors affecting metabolism and nutrient uptake of plants in CEA. Increasing light intensity can increase the concentration of nutritious phenolic compounds in many leafy greens[40]. Studies also showed that short-term supplemental lighting at the end of the production (EOP) can boost the nutritional quality and appearance of leafy greens[41]. However, current research, although extensive, is far from sufficient for optimizing production in CEA. The interaction between light spectrum and other key cardinal factors on crop performance remains largely untapped.

Soilless culture is a modern cultivation technology, which is used exclusively in CEA[42]. Hydroponics is a type of soilless culture and is often referred to as a solution culture where plant roots are immersed or partially immersed in a nutrient solution. The most widely used hydroponic systems are nutrient film technique (NFT) and deep-water culture (DWC) systems, while aeroponics is another variation of hydroponics, where plant roots are suspended in air and nutrient solution is misted onto plants roots intermittently. Generally, NFT and DWC are suitable for shallow root and short-term crops like leafy greens. NFT channels can vary greatly in size and length to suit different CEA production systems including vertical farms, while DWC is often used in greenhouses due to its heavy weight of solutions. Soilless substrate culture uses solid growing medium to anchor plant roots and is often used for long-term crops such as fruit vegetables and berry crops. In soilless substrate culture, many types of substrates such as coco coir, rockwool, etc. are used. Proper selection of growing substrates not only influences plant performance but also production costs. The key benefits of soilless substrate culture and hydroponics include the elimination of soil-borne diseases, prevention of soil fertility issues and salinity, and improved control and monitoring of nutrient levels. Over the past 40 years, advancements have focused on developing growing media with optimal physical, hydraulic, and chemical properties[43], standardizing substrate analysis, improving plant nutrition and automated irrigation systems[42], and developing various hydroponic systems[44]. Articles provide introductory reviews of CEA growing methods, artificial lighting, nutrition management, sensing technologies, automation, and substrates[45–48].

This perspective article explores key technological innovations poised to enhance CEA sustainability, emphasizing the necessity of transdisciplinary approaches. We examine integrated decision-making frameworks informed by comprehensive life cycle analysis, distributed indoor agriculture, electricity demand flexibility, Digital Twins, and engineered microbiomes and plants optimized for CEA systems. We also envision the role of CEA in sustainable and resilient communities and propose a transdisciplinary education approach for future CEA workforce development. The selection of the technological innovations was based on expert engineering judgment aiming at addressing major challenges in CEA.

Decision-making tools and emerging technologies in CEA

Integrated decision making based on life cycle analysis

Life cycle analysis guides decision making and policy for CEA (Fig. 1). Early-stage assessment across the life cycle of CEA is essential to support integrated decision-making and minimize costs[49]. Life cycle analysis can be used to optimize key CEA design factors[50], such as CEA size, location, envelope design, and heating, ventilation and air conditioning (HVAC) systems, and guide research and development to identify critical technologies for the CEA industry[51]. However, there is a lack of comprehensive life cycle analysis, evaluating potential environmental, economic and social impacts of the new CEA designs at different settings.

Most existing CEA life cycle analyses, such as life cycle assessment (LCA)[52], evaluate carbon footprints of resource use (e.g. fertilizer, energy, water)[26,31,53–59] or both economic and environmental performance[49,60–62] through case studies. Linking LCA to a bioeconomic model has been proposed for analyzing area-based farming policy[63]. Most studies represent current CEA technologies and have well-defined CEA in terms of size, system, and location. Thus, these studies are limited to comparing the current CEA prototypes to open-field agriculture but have limited impacts on supporting new designs and decision making for CEA.

Advocates for an ecological-economic approach that considers the environmental dimensions of meeting human needs highlight the need for a comprehensive approach to LCA that integrates economic, social, and environmental aspects[64]. Weidema[65] emphasizes the importance of integrating social aspects into LCA, while Arodudu et al.[66] suggests the use of tools and methodologies to bridge methodological gaps in LCA application to agro-bioenergy systems and to integrate agronomic options and life cycle thinking approaches.

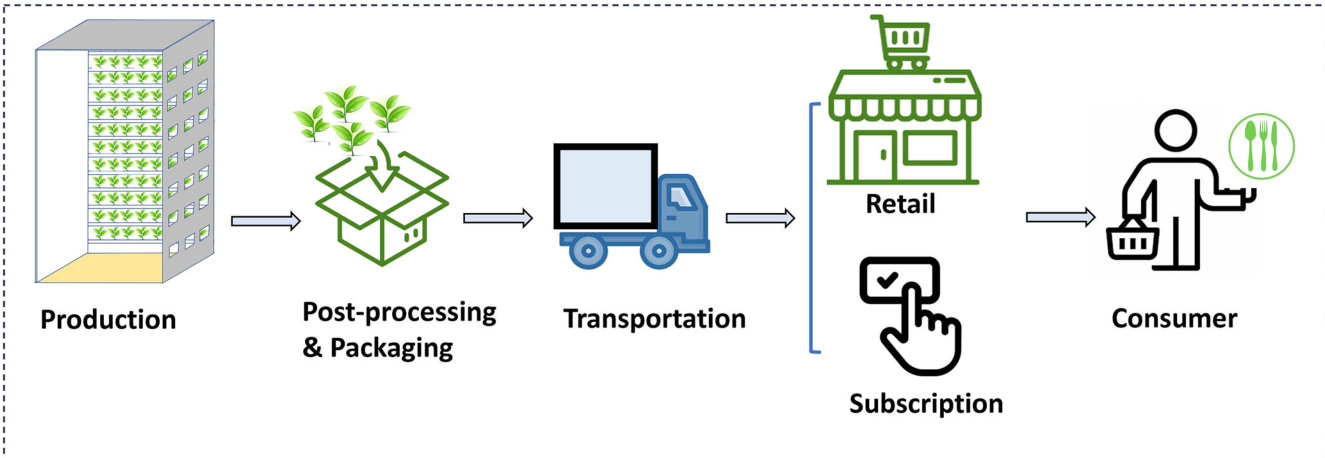

Fig. 1 | Life cycle analysis boundaries. This includes five key components as shown. **a** Crop production. **b** Post-processing and food packaging. **c** Transportation. **d** Food distribution. **e** End-use for consumers. Distributing food through retail community outlets is the most common practice. In the meantime, subscription services through e-delivery can be a better approach to reduce food waste in distribution.

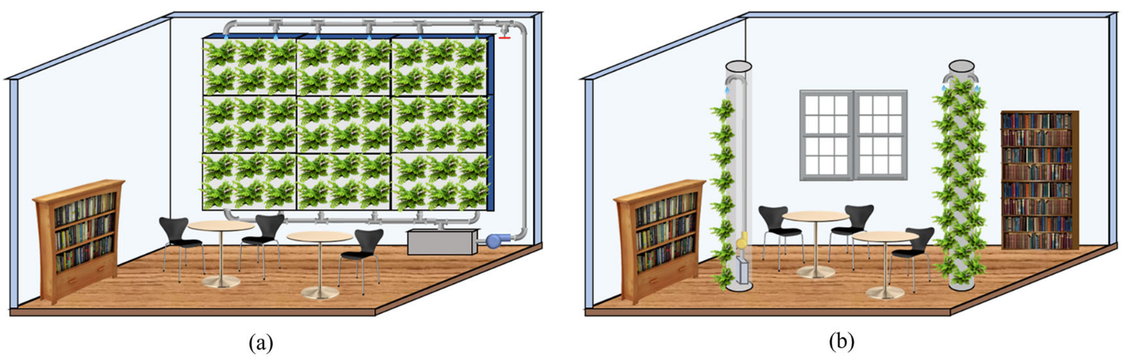

Fig. 2 | Demonstration of distributed indoor agriculture systems. **a** Distributed indoor agriculture system integrated with construction walls. **b** Distributed indoor agriculture system integrated with interior decorative columns.

LCA can be further applied to fulfill the CEA circular economy, supporting the development of sustainable strategies for CEA industry, reduction in waste and cost, and enhancement of resource efficiency at community scales. The reuse and recycling opportunities include waste heat utilization, CO_2 supply through co-location, water reuse and reclamation of nutrients from water treatment plants, and recycling of growing media and food packages[67]. Various case studies report their utilization of waste heat from combined heat and power plants[68–70], data centers[71–74], and plant factories[75]. Indoor farms reuse low-quality energy, in the form of warm water or air in a temperature range of 30–47 °C. Recirculating irrigation water has the potential to reduce water consumption by 20–40% and fertilizer costs by 40–50%[76]. Water reuse for crop growth conserves freshwater, promotes water circularity, and reduces the total need for chemical fertilizers[77]. Defining the water treatment and nutrient reclamation requirements for crop growth is an important research question for CEA[78]. Potential contamination risks such as microbial pathogens and chemical content should also be considered for irrigation[79]. Although waste resources may be limited by location, it is possible to create a CEA ecosystem through strategic planning of businesses and infrastructure within communities. The evaluation of the planning scenarios can be based on comprehensive life cycle analysis, integrating economic, social, and environmental aspects.

Distributed indoor agriculture

Distributed indoor agriculture (DIA) systems within buildings can support crop cultivation using hydroponic techniques—such as NFT and DWC, as discussed in Section "Current CEA technologies". Each DIA system (Fig. 2) is equipped with integrated hardware and software solutions, including controls of grow lights and irrigation, monitoring of crop growth, and diagnosis of issues related to crop health and system operation.

Indoor living walls, a foundational prototype of the DIA system, have gained popularity by bringing nature indoors[80], and indoor plants have become highly desirable with the rise of remote work[81]. Studies show measurable benefits of these systems on occupants' thermal comfort and building cooling load reduction[82–84]. With living walls, the cooling setpoint can be increased by 0.9 K and still satisfy thermal comfort needs for the majority of the occupants[83]. In an experimental study of a hall with a floor area of 520 ft^2 that was not equipped with air conditioning, an average temperature reduction of 4 K was observed[85]. In addition, indoor plants demonstrate the capability to improve indoor air quality[86–93], productivity and creativity[94], while reducing noise levels[95], the negative effects of visual glare[96,97], stresses[98], and discomfort symptoms[99,100]. Plant leaves and their microbes purify indoor air through phytoremediation, absorbing pollutants via leaf stomata and degrading them through plant metabolism[101]. Plant elements like leaves and twigs reflect, scatter, and attenuate sound through mechanical vibration. A study of a 2.4 m^2 living wall in a space with floor area of 19.6 m^2 found a weighted sound reduction index of 15 dB and a weighted sound absorption coefficient of 0.40[95]. Moreover, people were more productive (12% quicker reaction time on a computer task) and less stressed (systolic blood pressure readings lowered by one to four units)[94].

Can DIA systems be a potential integrated solution to food resilience, better indoor environmental quality, energy efficiency, and well-being? Broadly speaking, there are four broad markets to target (1) offices; (2)

institutions; (3) hospitality; and (4) residential buildings. Dedicating 1% of floor area identified in the Commercial Building Energy Consumption Survey (CBECS)[102] and Residential Energy Consumption Survey (RECS)[103] to growing lettuce in existing buildings has a potential yield of 5.1–70.4 kg fresh weight lettuce per capita per growing cycle (about four weeks) based on the reported lettuce yield (6.9–95 kg fresh weight) per growing floor area (m^2)[104]. This potential yield is much higher than the U.S. per capita consumption of fresh romaine and leaf lettuce (5.8 kg) in 2022[105]. DIA and CEA are distinct and potentially competitive models for food production, but their co-existence can provide mutual benefits. Successful DIA demonstrations promote mass-market acceptance of hydroponically grown foods through social impacts, public education, and easy accessibility of technology.

CEA electricity demand flexibility

Connecting CEA with microgrids can not only reduce CEA's carbon footprint but also contribute to stabilizing microgrids through demand response and frequency control. Electricity demand from lights and HVAC systems and the associated carbon footprints have been significant for indoor vertical farms. CEA can be strategically co-located in areas with existing microgrid infrastructure or where dynamic electricity pricing creates opportunities for cost savings and load flexibility. Shifting LED lights from continuous to intermittent operation was implemented to reduce operational costs by responding to daily electricity price fluctuations[106,107].

CEA can serve as a demand-side dispatchable load for microgrids to reduce the volatility of renewable energy resources (Fig. 3). Stable operation of electric systems requires frequency regulation; providing frequency regulation from demand side resources mitigates technical, economic, and political challenges[108]. Existing studies have tested the feasibility of using HVAC equipment as dispatchable loads on the demand side[109–111]. Due to the high volatility of such distributed energy resources (DERs) as wind turbines, photovoltaics, and hydroelectricity, balancing renewable energy generation and demands for microgrids is expensive in comparison to traditional power grid frequency regulation. CEA can potentially serve as an important dispatchable load on the demand side if crops can tolerate certain lighting fluctuations. Dynamic environmental variations trigger plants' physiological response, yet they can maintain diurnal leaf carbon gain in comparison with plant growth in constant environments[112]. Further research is needed on how variations of LED light and temperature induced by dynamic variations in price signals from microgrids affect crop yield and quality.

Digital twins in CEA

A CEA Digital Twin (DT) framework integrates computer vision, edge computing, AI-enabled predictive analytics, and optimal control technologies (Fig. 4), forecasting and optimizing the behavior of the physical asset (crops) and resource management. DT frameworks have been explored in various contexts in CEA, including monitoring DT for tracking subsystems[113], predictive DT for optimizing production and resource use efficiency[114,115], supply chain DT to optimize agrifood supply chain[116], DT for aquaponics production facilities[117], and visualization DT[118].

Computer vision is the key component to acquire crop growth information and provide feedback to update crop model parameters for resource optimization[119–122]. Studies have focused on developing growth forecasting based on early-stage growth images using spatial transformation[123] and spatial-temporal attention mechanisms[124]. State-of-the-art algorithms, such as YOLO series[119], Mask-RCNN[125], and Deepabv3+[126], have been employed for growth monitoring, yield prediction, and spacing optimization. However, image-based systems encounter limitations. Occlusions and complex canopies create challenges in developing automation solutions for plant monitoring. Thus, advanced algorithms and approaches such as 3D reconstruction (via Neural Radiance Fields[127], and Gaussian Splatting), and geometric DT[128,129] are needed to enhance crop growth monitoring solutions for CEA. Furthermore, multispectral and hyperspectral imaging systems have been deployed to determine the nutrient concentration in CEA produce so that growers can develop mitigation strategies before deficiency symptoms arise[130–133]. However, the detection accuracy is limited due to the extremely complex workspace. Most deep learning-based networks require image normalization before images are input to the network, reducing the feature details and decreasing detection accuracy.

Intelligent climate controllers, driven by microclimate data, have advanced optimal energy use management. AI algorithms, such as reinforcement learning have been explored to optimize energy and water use in greenhouses[134]. A wide range of control algorithms has been explored to optimize variables such as light intensity, air velocity, shade curtain, vapor pressure deficits, and CO_2 levels to minimize energy costs[135–138]. In addition,

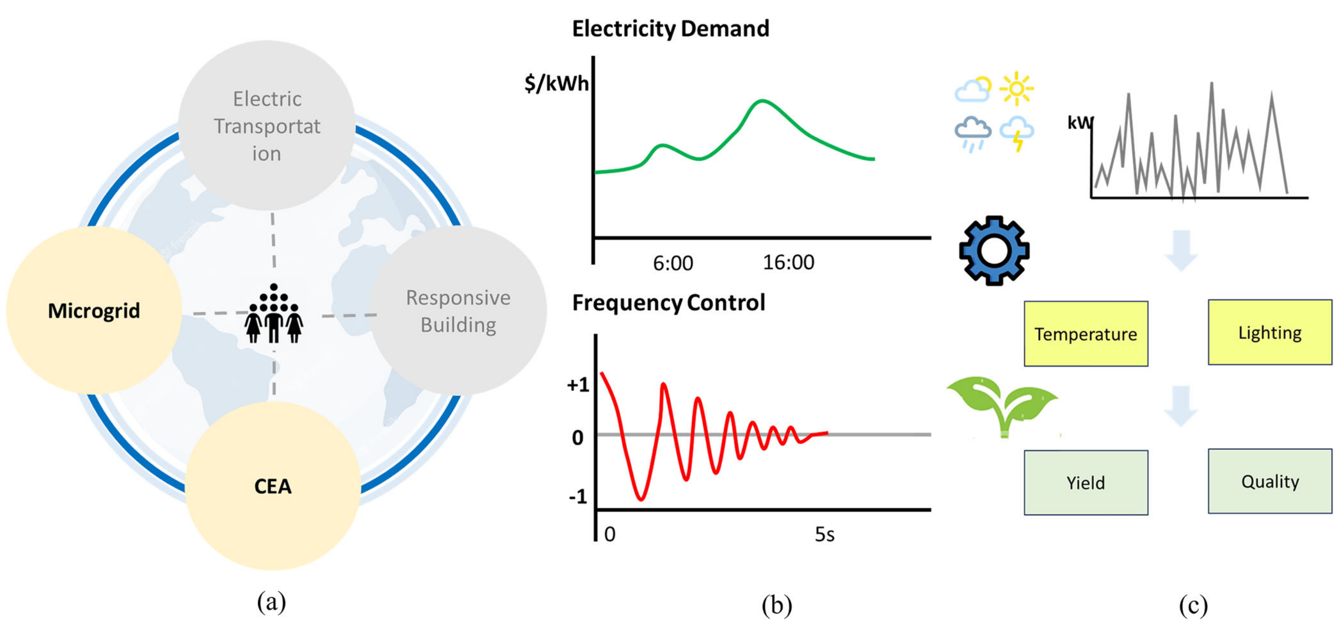

Fig. 3 | Connection between microgrid and CEA. **a** Both microgrid and CEA are considered as modern infrastructures in future communities. **b** CEA as dispatchable loads for ancillary services of utility companies through demand response and frequency control. **c** Future research direction on the impacts of the variations of temperature and lighting intensities in response to volatility of renewable energy systems on crop yield and quality.

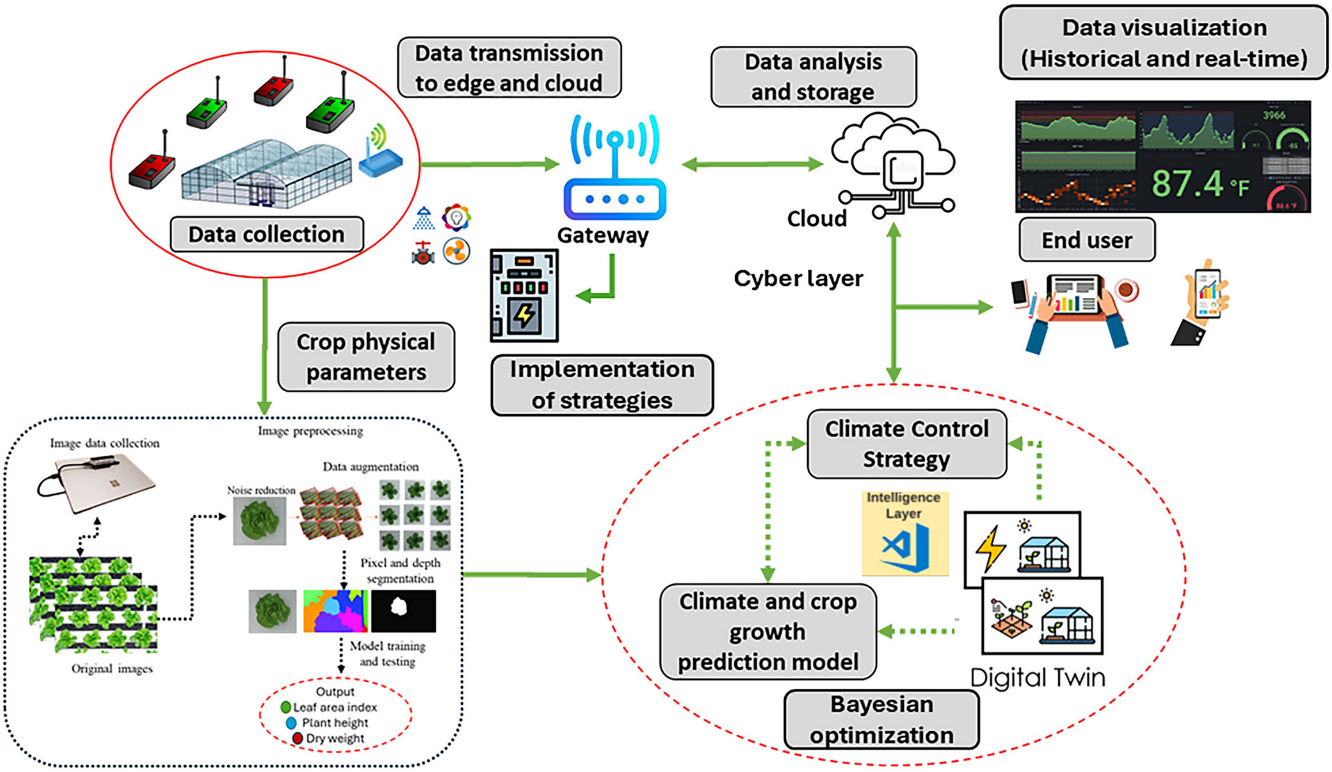

Fig. 4 | A schematic illustration of a Digital Twin (DT) framework for CEA. The DT framework integrates computer vision-based crop monitoring, edge and cloud data processing, AI-driven climate and growth prediction models, and Bayesian optimization for dynamic climate control. Real-time data acquisition and feedback enable continuous model calibration, facilitating adaptive resource management, crop growth forecasting, and energy optimization under variable environmental conditions.

DT requests vast amounts of data, subject to issues like inaccuracies and cyberattacks. Blockchain has been applied in CEA applications[139–141] to enhance information security.

A major obstacle to optimal outcomes in CEA lies in real-time crops' response to environmental conditions and thus decoupled crop growth and resource optimization[142]. Although studies have been conducted for optimal resource allocation under fixed microclimate conditions[143–145], forecasting growth based on training data from fixed conditions may limit its applicability in real CEA environments with dynamic climate conditions. A real-time feedback DT system must assess forecast accuracy and adjust model parameters, leading to efficient decision support for growers to optimize production and energy use.

Microbiome management in CEA

Growing plants in hydroponics rather than soil dramatically changes the challenges. One important facet of plant physiology and plant health is the contribution of the plant microbiota, which represents a largely untapped opportunity[146]. Plant growth-promoting bacteria (PGPB) reside in or around plants and can act as biostimulants, biofertilizers, and bioprotectants[147]. Plant-associated beneficial microorganisms – e.g., bacteria and fungi – promote growth, nutrient uptake, stress tolerance, and resistance to pathogens[148]. However, many plant-growth-promoting microbes found in soil cannot make the transition to hydroponic environments[149]. Moreover, many PGPB products are developed for field application and have not been optimized for specific conditions of CEA which include dense cropping of specifically optimized crops, controlled water and climate systems, and integrated sensors and controllers. While hydroponics has a range of advantages over soil-based cultivation, one of the disadvantages is the fast spread of infectious diseases due to the recirculating nature of nutrient solution in the whole system. In such a case, PGPB may offer a unique solution in hydroponic systems by sensing and preventing pathogen outbreaks, improving access to nutrients and tolerance to biotic and abiotic stresses and increasing crop yield. To date, there are reports that PGPB promotes plant growth in various hydroponic systems. For example, *Pseudomonas psychrotolerans* IALR632 increased shoot and root growth of green Oakleaf lettuce grown in nutrient film technique (NFT) in the greenhouse, indoor vertical NFT, and a deep-water culture system[150].

Another group of beneficial microbial-based microorganisms is arbuscular mycorrhizal fungi (AMF). AMF is known to form AMF-host plant symbiosis with more than 80% of plant species[151]. The primary positive impacts of AMF symbiosis are increasing availability of both macro- and micro-nutrients, increasing photosynthetic rate, and enhancing tolerance to stressful conditions through augmentation of antioxidant defense system. A recent study by Caser et al.[152] for saffron in soilless systems in a glasshouse indicated that inoculation with one AMF species (*Rhizophagus intraradices*) or a mixture of *R. intraradices* and *Funneliformis mosseae* increased spice quality as evidenced by a superior content of several health-promoting compounds (polyphenols, anthocyanins, vitamin C, and antioxidant activity) in one cycle of growth in soilless systems compared to open field production, while spice yield was similar to that of open field. These results improve our understanding of microbial communities in soilless media. Nevertheless, such information is still limited, and future studies are needed to fully understand and optimize the benefits of microbes under controlled environments. There are also advanced opportunities for genetically engineering these communities for enhanced properties for the plant; better association with the plant and survival/persistence in the hydroponic environment, and for coupling to CEA control systems by reporting on water, microbiome and plant health through expression of environmentally-sensitive fluorescent and volatile organic reporters[153]. A growing body of literature has focused on defining, engineering and using laboratory evolution to evolve such synthetic communities for plants in both soil and artificial conditions[154,155] —a focused effort to co-design microbial communities supporting optimized plants and coupling with control systems.

Engineered plants for CEA

Transgenic crops have revolutionized the scale and nature of agriculture; however, such efforts are largely focused on addressing producer-facing challenges associated with traditional methods of growing crops in fields (i.e., herbicide tolerance, insect resistance). Crops grown in CEAs may shift the focus of engineering efforts towards other consumer-facing traits that may benefit from indoor growth. Growing plants that are engineered to improve human health through the enhanced delivery of key phytonutrients has been a key pillar in plant engineering efforts[156,157]. Complex natural products ranging from edible health compounds to plant-derived pharmaceuticals may be developed as interesting targets for transgenic plants grown in CEA[158–161]. Nutrient management in CEA can significantly enhance the vitamin content in crops through precise control and optimization of nutrient solutions that meet the specific requirements of various plant species and growth stages. This targeted approach enables growers to enhance the uptake of specific nutrients that are precursors to vitamins, leading to increased vitamin content in crops[162]. One regulatory challenge of field-grown crops is the concern of outcrossing of transgenes; thus, the large-scale indoor growth of transgenic crops in CEA may open the door to safer implementation and growth of engineered plants, which may also expand the range of traits that could be pursued.

Optimizing and redesigning plant architecture within confined space limitations has the opportunity to dramatically enhance yield of indoor-grown crops. Kwon et al. leveraged CRISPR-Cas9 genome editing to target and manipulate the physiology of tomato plants by engineering highly compact and rapid flowering plants[163]. The optimization of plant stature may enable the custom development of CEAs that are more space efficient and enable higher yield per footprint. The implications of such efforts are aligned with the challenges associated with growing plants indoors with limited space.

The role of CEA in communities

Community and CEA

CEA benefits communities from shortened food miles and better food quality to opportunities for education and employment (Fig. 5). Community-based CEA inherits demonstrated benefits from community gardens but offers a year-long growing environment and the opportunity to revitalize communities by repurposing abandoned warehouses. This industry offers employment opportunities for community members with physical or mental disabilities[164] and educational opportunities for next generations. The involvements of community gardens increase students' choice of healthy diet and their number of weekly physical activities[165]. In less favorable climate states, indoor farms enable school-age children to have year-round access to fresh salads. Akin to traditional community gardens, community-based CEA farms provide shared venues for community members to exchange culture and food knowledge and cultivating healthy social environments[166,167]. Studies show that the social interactions and quality of community gardens benefit elders' well-being[168].

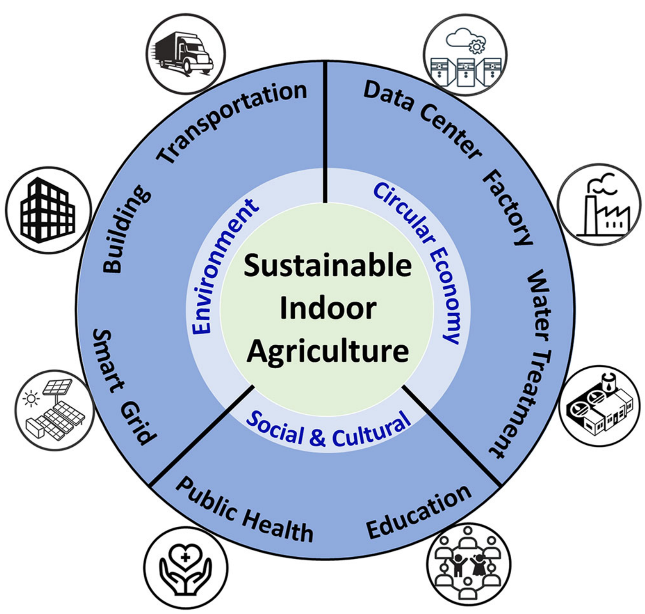

Fig. 5 | The interaction between CEA and other infrastructure in future communities. CEA can be integrated with building design and operation to provide food security through a shorter and more resilient supply chain and enhance environmental quality. Resources such as heat, CO_2, reclaimed nutrients and water required in CEA operation can be supplied with byproducts from combined heat and power, data center, factory, or water treatment plant.

CEA has strong synergy with urban agriculture initiatives, offering potential benefits in food security, sustainability, and local economic development. City-level programs such as Grow Boston and FarmPhilly in Philadelphia actively support CEA innovations and local food access. However, implementing CEA in dense urban environments introduces critical challenges, including prohibitive land costs, limited available space, and existing infrastructure constraints. Community-based CEA must therefore take into account not only logistics, crop selection, and resource efficiency but also the spatial and economic feasibility of deployment. These systems can align with urban planning frameworks such as the 15-min neighborhood concept, which emphasizes localized access to services[169]. Large-scale community modeling tools—integrating food demand, carbon emissions, energy flows, and socioeconomic impacts—can inform urban-scale CEA design and guide implementation strategies.

CEA education and workforce development

A holistic transdisciplinary education approach across agriculture, architecture, engineering, and business should be taken to design a structured curriculum or technical training for CEA and associated courses for higher education. The future success of CEA largely depends on training diverse workers fluent in engineering, plant science, and business management and skilled in working in transdisciplinary, collaborative environments. However, such advanced technological training for the future CEA workforce[170–172] is rare in the US and other countries[173,174], because such training is beyond traditional agriculture production and management and cannot be completed by a single traditional program such as plant science or horticulture[170].

Engaging K-12 educators in CEA scientific research as professional development is essential to cultivate the interests of the next generations in CEA or STEM in general. The "Train the Trainers" model has proved that teachers' professional development boosts students' achievement[175]. Translating scientific research experience and knowledge in CEA into K-12 classroom education requires rapport with the K-12 education community on shared learning experience and scientists in higher education on technical skill training for teachers. Teachers have the opportunity to bring students hands-on experiences in school greenhouses and indoor growing facilities based on state-of-the-art research in CEA.

Conclusion

CEA represents many opportunities for future indoor agriculture and provides partial potential solutions to such grand challenges as food and nutrition insecurity. CEA allows crops to grow year-round under uncertain climate conditions, shortens food miles and associated food waste through transportation, and offers social and health benefits to communities. Innovative technologies are essential to make CEA sustainable. From a carbon footprint perspective, a significant reduction in carbon emissions of CEA operation is necessary. Technologies for collecting and distributing natural solar light in buildings can potentially reduce the electricity demand of intensive LED light through novel architectural designs. Plant photosynthesis efficiency[176] can be improved through engineered plants and microbiome management, which may allow plants to grow in a relatively dark environment and reduce lighting demands. Robotics in CEA or agriculture in general may replace repetitive works such as pruning, planting and harvesting and require that the workers in agriculture have advanced skills. While CEA offers benefits, both open-field agriculture and CEA can complement each other, with CEA focusing on high-value and fresh produce, particularly in regions with a less favorable climate, while open field agriculture provides high energy demanding staple crops with relatively long lifespans. A holistic transdisciplinary approach is essential in both research and education to achieve sustainable, resilient, and scalable future CEA and would make a critical contribution and transform the current CEA industry.

Data availability

No datasets were generated or analyzed during the current study.

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Author contributions

L.W., L.N., and A.A. designed the concept and overall structure; L.W. wrote the overview, Section "Distributed indoor agriculture", and conclusion and prepared Figs. 1–3 and 5; G.N. wrote Section "Current CEA technologies"; L.W. and S.V.D.S. wrote section "Integrated decision making based on life cycle analysis"; L.N., M.A.P. and L.W. wrote Section "CEA electricity demand flexibility"; A.Z. and B.G. wrote Section "Digital twins in CEA" and A.Z. prepared Fig. 4; A.A., P.S. and G.N. wrote Section "Microbiome management in CEA"; P.S. wrote Section "Engineered plants for CEA"; L.W. and L.N. wrote Section "The role of CEA in communities"; all authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to Liping Wang, Leslie Norford or Adam Arkin.

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