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Controlled Environment Agriculture: Revolutionizing Field Crop Production

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Abstract: Climate change has intensified the challenge of ensuring global food security, prompting innovations beyond traditional open-field farming. Field crops such as wheat, rice, and maize are global staples, but their production is threatened by extreme weather, water scarcity, and land degradation. Controlled Environment Agriculture (CEA) offers a promising solution by creating fully managed systems where light, temperature, humidity, and nutrients are precisely controlled. Unlike conventional farming, CEA not only reduces weather dependence but also enhances resource efficiency and secures reliable crop production even in adverse climates. Although the idea of protected cultivation has ancient roots, modern CEA technologies have expanded its potential far beyond traditional methods. NASA first developed plant-growth chambers, which later advanced into modules such as Veggie and the Advanced Plant Habitat on the International Space Station. These demonstrated successful crop cultivation in extreme environments [1]. CEA can be classified based on technology, structure, growing medium, and production systems. Recent advances in these areas aim to enhance sustainability and reduce environmental impacts. Key innovations include hydroponics, aquaponics, and high-tunnel farming. Automated greenhouses further improve efficiency through sensors and smart controls. Agrivoltaics integrates crop cultivation with solar energy harvesting, enabling dual land use and lowering reliance on non-renewable resources [2]. Singh *et al*. [3] developed a cost-effective Climate-Smart Hydroponic Chamber (CSHC) at ICAR-IGFRI, Jhansi, to address fodder scarcity in semi-arid regions. The chamber maintained optimal growth conditions (23-28 °C, 87-90% RH) with a cooling efficiency of 78%, ensuring high-quality fodder production throughout the year. Importantly, the structure was economically viable and fabricated with locally available materials. Its cost was only a fraction of conventional systems, making it a scalable solution for smallholder farmers to improve livestock feed security. Despite its promise, CEA faces challenges such as high energy demand, infrastructure costs, and the need for skilled management. However, opportunities lie in technological innovations, renewable energy integration, and the scaling of affordable models like the CSHC. Overall, CEA represents a paradigm shift in agriculture, offering pathways toward resilient, resource-efficient, and climate-smart food production.

Key words: Controlled environment agriculture, agrivoltaics, climate-smart hydroponic chamber.

1. Introduction

Global food insecurity is becoming increasingly severe as climate change continues to disrupt agricultural systems. Rising temperatures, extreme weather events, and soil degradation are threatening the production of staple crops, making traditional farming methods less sustainable for a rapidly growing global population [4]. By 2050, the world's population is expected to reach 9.7 billion, which will require at least 70% more food than what we produce today. However, conventional farming is struggling to adapt to these environmental challenges, putting the stability of future food supplies at serious risk [5]. To address these growing challenges, innovative farming methods that move beyond traditional practices are becoming increasingly essential. One promising approach is Controlled Environment Agriculture (CEA), a modern, climate-smart farming system that allows crops to be grown in carefully managed and optimized conditions. By protecting plants from the uncertainties of climate change, CEA offers a sustainable and reliable solution for ensuring consistent food production.

Controlled Environment Agriculture (CEA): Controlled Environment Agriculture (CEA) is defined as the practice of growing crops in a closed, indoor

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environment and under controlled conditions such as vertical farms or greenhouses, where variables like light, humidity, and temperature can be carefully controlled.

Conventional field crops such as rice and wheat are highly vulnerable to unpredictable weather patterns. With the increasing impacts of climate change, traditional open-field farming is becoming less practical and more uncertain. Our heavy reliance on these systems leaves food production exposed to environmental instability. In contrast, Controlled Environment Agriculture (CEA) provides a dependable alternative, ensuring consistent yields and enhancing food security even amid changing climatic conditions [6].

2. Open-Field Agriculture *vs* CEA

Traditional open-field farming is often vulnerable to unpredictable weather, resulting in fluctuating yields and inefficient use of resources. In contrast, Controlled Environment Agriculture (CEA) creates a stable and precisely managed setting where factors like humidity, light, and temperature are carefully controlled. This approach ensures consistent crop quality, higher productivity, and better resource efficiency. Moreover, by enabling food production closer to Urban centers, CEA helps reduce food miles supporting both environmental sustainability and long-term food security [7].

Figure 1 Effects of climate change.

Figure 2 Rice grown in a walk-in plant growth room at the Sir David Read Controlled Environment Facility in the UK [8].

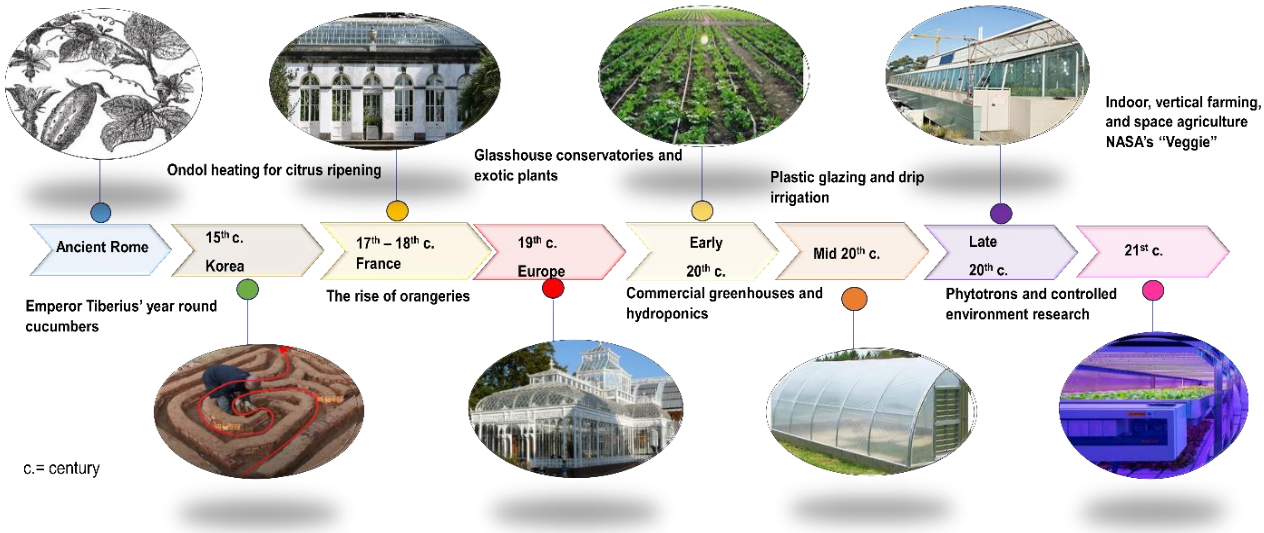

Figure 3 Evolution of CEA.

3. Evolution of CEA

Over the centuries, humans have continually sought ways to grow food beyond the limits of seasons and climate, leading to the evolution of **Controlled Environment Agriculture (CEA)**. Its origin trace back to ancient Rome, where Emperor Tiberius' gardeners used *specularia*, protective structures with translucent covers to grow cucumbers year-round. In 15th-century Korea, farmers used *ondol* heating systems to ripen mandarins despite the harsh winter cold. By the 17th and 18th centuries, European aristocrats were building orangeries to shield citrus trees from freezing temperatures. The 19th century then marked a major step forward with the creation of glass and iron conservatories, laying the foundation for the modern greenhouse systems we know today [9].

Over time, Controlled Environment Agriculture (CEA) evolved from being a luxury practice to a practical farming solution during the 20th century. Innovations such as drip irrigation, plastic greenhouse films, and hydroponic systems made CEA more affordable and efficient. During the mid to late 20th century, specialized research centers known as *phytotrons* deepened scientific understanding of how plants interact with their environments. With modern advancements in automation, artificial intelligence, and LED lighting, CEA has now expanded into vertical farming, indoor agriculture, and even space-based experiments [10]. This evolution reflects humanity's ongoing pursuit of resilient, efficient, and sustainable food production, positioning CEA as a vital part of modern agriculture. Controlled Environment Agriculture (CEA) has extended its reach beyond Earth through the development of space agriculture. A major milestone was achieved in 2014 when NASA launched the "Veggie" plant growth unit aboard the International Space Station, allowing astronauts to cultivate fresh produce in orbit [11]. This remarkable achievement not only improves astronauts' health and nutrition during long space missions but also proves that CEA technologies can thrive even in the most extreme and unfamiliar conditions. Research like this is crucial for the future of space exploration, paving the way for sustainable human living beyond Earth.

4. Environmental Control Variables

In Controlled Environment Agriculture (CEA), managing environmental factors is key to promoting healthy plant growth and achieving high yields. Air and root zone temperatures directly influence photosynthesis, respiration, germination, and nutrient uptake, while relative humidity and vapor pressure deficit

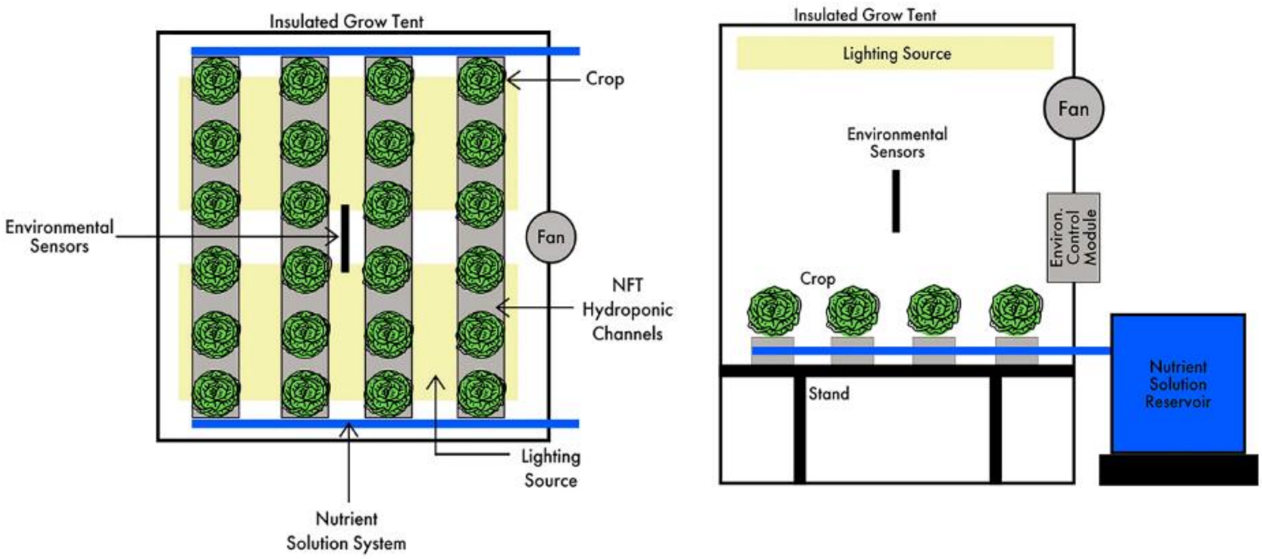

Figure 4 Top view (left) and front view (right) of an illustration of the primary elements of a Controlled Environment Agriculture (CEA) setup.

(VPD) help regulate transpiration, stomatal activity, and disease prevention. Light intensity, spectrum, and photoperiod also play crucial roles, shaping photosynthesis, plant structure, and flowering cycles. Adequate airflow is essential to distribute heat and CO_2 evenly and to minimize disease risks. To maintain these conditions, growers use a range of tools from e equipment like fans, heaters, vents, and shade cloths to advanced technologies such as CO_2 injectors, LED lighting, automated HVAC systems, and climate control software. By carefully adjusting these variables, CEA systems create optimal microclimates that boost productivity, improve resource efficiency, and ensure consistent, high-quality crop production year-round [12].

5. Main Elements Needed for CEA

According to Garcia *et al*. [13], a Controlled Environment Agriculture (CEA) system typically relies on six key components. First, a well-insulated building with opaque walls helps maintain a stable environment. Second, a multi-layered structure provides space for crops and their lighting systems. Third, pumps help manage humidity and remove excess heat generated by lights. Fourth, a carbon dioxide delivery system boosts photosynthesis and plant growth. Fifth, an efficient nutrient delivery system ensures crops receive the right nourishment. Finally, environmental control systems regulate factors like pH and power levels to maintain proper nutrient circulation and overall system stability.

6. Classification of CEA

CEA systems can be classified according to their structure, the technology or level of automation they use, the type of growing medium, and the overall production system [12].

Controlled Environment Agriculture (CEA) can be classified based on the type of structure used. Greenhouses, for example, combine natural sunlight with climate controls, while indoor farms and vertical systems rely entirely on artificial lighting. Simpler structures such as shade houses, screen houses, and high tunnels provide partial protection, helping to extend the growing season and reduce stress caused by environmental fluctuations.

The second way CEA systems are classified is by their level of technology and automation. Low-tech systems rely on manual tools such as fans, vents, and shade cloths to manage the growing environment. In

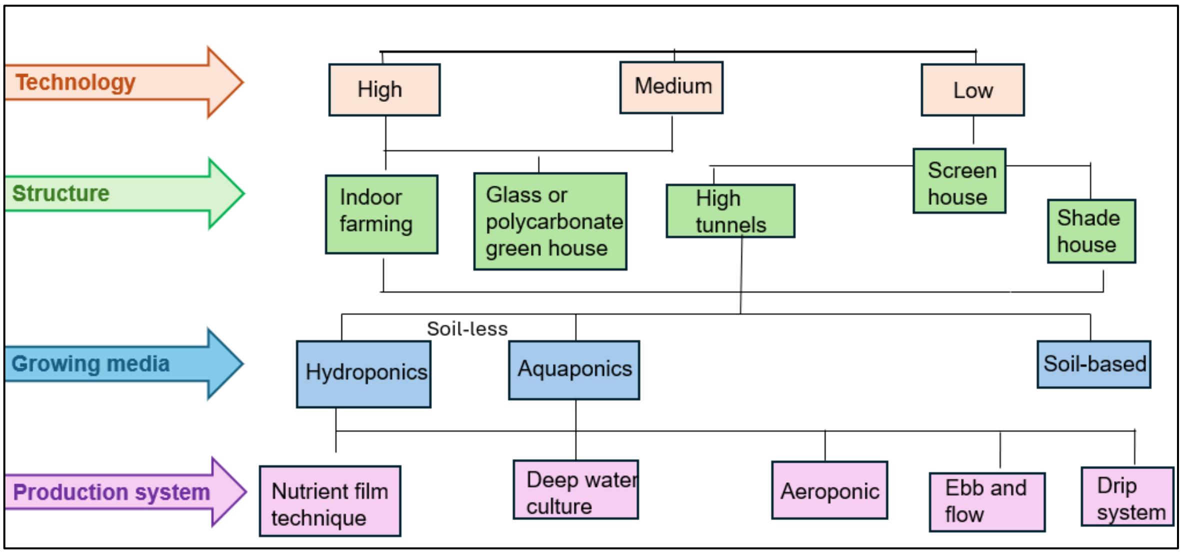

Figure 5 Classification of CEA.

contrast, high-tech systems use advanced sensors, automated irrigation, HVAC systems, and computer-controlled adjustments to maintain precise and optimal growing conditions.

CEA systems can also be classified based on the type of growing medium. Some systems use traditional soil-based methods, particularly in tunnels or shade structures. More advanced systems, however, rely on soilless media such as coco coir, perlite, or rockwool. In certain setups, plant roots are even suspended in nutrient solutions without any solid medium at all.

CEA systems can also be categorized by their production methods. Hydroponics is the most common approach and includes techniques like the Nutrient Film Technique (NFT), drip irrigation, ebb and flow, and deep-water culture. Aeroponics delivers nutrient-rich mist directly to plant roots, while aquaponics combines aquaculture with plant cultivation, using fish waste as a natural fertilizer for the crops.

7. Technologies Driving CEA

Advances in technology have made it possible to precisely control growing conditions, driving the rise of Controlled Environment Agriculture (CEA). Structures like high tunnels and plastic covers help extend the growing season, protect crops from extreme weather, and provide a degree of environmental control. The productivity of automated greenhouses is further enhanced through integrated systems such as HVAC (heating, ventilation, and air conditioning), LED lighting, and advanced climate management tools. Techniques like hydroponics and aeroponics, which deliver water and nutrients directly to plant roots, improve both crop yields and resource efficiency. Another innovative approach, agrivoltaics, combines solar energy production with crop cultivation, providing a sustainable way to meet both energy and food needs simultaneously.

8. Energy Efficiency and Sustainability

Controlled Environment Agriculture (CEA) systems often require significant energy to regulate environmental conditions, particularly when relying on artificial lighting. This environmental impact can be mitigated by using renewable energy sources such as solar power, geothermal systems, and advanced passive cooling techniques. Because non-renewable resources are unsustainable, their use is discouraged in CEA. Prioritizing renewable energy is therefore a key strategy for improving both the sustainability and energy efficiency of these systems [14].

Figure 6 The agrivoltaics farm set up by CIAL, located close to the airport's cargo terminal.

9. Agrivoltaics

Agrivoltaics combines crop production, pastures, or other beneficial vegetation with solar energy systems to make the most efficient use of land. This can be achieved in several ways, such as growing plants under elevated solar panels, placing photovoltaic modules on greenhouse roofs, or cultivating crops between rows of solar panels. When combined with Controlled Environment Agriculture (CEA), agrivoltaics allows precise control over light, temperature, and humidity, while simultaneously producing crops and renewable energy. This approach improves land-use efficiency, reduces water loss through evaporation, and shields plants from heat stress by providing controlled shading. It also supports better water management, higher potential yields, lower greenhouse gas emissions, and increased resilience to climate change.

A real-world example is the photovoltaic greenhouses at Cochin International Airport Ltd. (CIAL). CIAL has now expanded its agrivoltaic farming to 20 acres, making it the largest project of its kind in India and setting a new benchmark for sustainable agriculture [2, 15].

Climate Smart Hydroponic Chamber: Singh *et al.* [3] studied the Climate Smart Hydroponic Chamber (CSHC) as a solution for efficiently producing green fodder in semi-arid regions with limited resources. The CSHC proved highly effective in maintaining an ideal environment for plant growth. Soaking seeds for 12 hours and using a seed loading of 600 g/ft^2 resulted in the highest fodder yield of 2.58 kg/ft^2. This approach not only boosts livestock productivity in semi-arid areas but is also both economically viable and efficient. As a result, it represents a promising innovation that could enable year-round green fodder production, offering a reliable and practical solution for farmers with limited resources.

Positive impact of artificial light and hydroponics on yield and quality of wheat: At the Plant Technology Center of the Technical University of Munich in Freising, Germany, Bassu *et al.* [16] studied how soilless controlled environment agriculture (CEA) systems, artificial lighting, and various controlled conditions affected wheat yield and grain quality for bread-making. They also compared the growth of wheat in these controlled systems with wheat grown under traditional open-field conditions. Wheat grown in controlled environment agriculture yielded more grain than wheat grown in the field. In addition, bread-making quality improved under these controlled conditions. The regulated environment not only enhanced overall grain quality but also led to subtle changes in protein composition.

10. Benefits of CEA in Field Crop

Production

Prolonged growing season — CEA systems allow crops to be grown year-round by carefully controlling temperature, humidity, and light, minimizing the effects of seasonal changes and extreme weather [17].

Enhanced yield and crop quality — By providing optimal growing conditions, CEA systems boost productivity and ensure consistent crop quality, while also reducing the fluctuations commonly seen in traditional open-field farming.

Risk reduction — CEA protects crops from harsh weather, pests, and diseases by shielding them from environmental stresses and climate-related fluctuations, reducing the risk of yield losses.

Improved resource use efficiency — Controlled systems optimize the use of energy, water, and nutrients, lowering consumption while boosting overall efficiency [18].

Localized and sustainable production — Growing crops near consumer markets ensures a year-round supply of fresh produce while also cutting emissions and reducing losses that occur during long distance transportation.

11. Challenges and Limitations of CEA

High initial investment: Setting up CEA systems involves higher initial costs than traditional farming, as it requires advanced structures and technology.

High operating costs: Running and maintaining CEA facilities requires substantial energy, particularly for automated systems, lighting, and climate control.

Economic constraints: Because of the high setup and operating costs, CEA may not be a financially practical option for small-scale or resource-limited farmers.

Requirement of specialized skills: CEA systems need skilled staff with technical expertise to manage environmental conditions and ensure optimal crop growth.

Limited crop variety: Not all crops are suitable for indoor cultivation; plants with large canopies or specific ecological needs can be difficult to grow in controlled environments.

12. Future prospects

Renewable energy adoption: Energy demand is a major challenge for CEA, but integrating renewable energy with smart energy management can help create a low-carbon, climate-resilient food production system.

Advancement in automation: With rising labour costs and a shortage of workers, automation has become essential in agriculture. AI-driven technologies are transforming CEA by performing tasks more accurately and efficiently.

Climate resilient farming: CEA, as a climate-smart farming approach, reduces the risks of climate variability by providing stable and carefully controlled growing conditions.

Supportive government policies: Greater government funding and support programs can play a key role in promoting the adoption and expansion of CEA technologies.

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