



Controlled Agriculture Environment: A Sustainable Approach to Modern Food Production

*Bharathi G.¹, Sunil C. M.², Yogananda S. B.³ and Ramesh Y. M.⁴

¹PG Scholar, Department of Agronomy, College of Agriculture, V.C. Farm, Mandya, University of Agricultural Sciences, Mandya, Karnataka-571405

²Junior Agronomist, AICRP on Small Millets, ZARS, V.C. Farm, Mandya, University of Agricultural Sciences, Mandya, Karnataka-571405

³Head of the Department, Department of Agronomy, University of Agricultural Sciences, Mandya, Karnataka-571405

⁴Assistant Professor, Department of Agronomy, University of Agricultural Sciences, Mandya, Karnataka-571405

*Corresponding Author's email: bharathig1432@gmail.com

Controlled Agriculture Environment (CAE) has emerged as a modern solution to address critical lacunae in conventional farming, such as climate variability, resource inefficiency and inconsistent crop yields. Traditional agricultural practices often face challenges related to unpredictable weather, soil degradation and water scarcity, which limit productivity and sustainability. CAE overcomes these gaps by enabling precise control of environmental factors like temperature, humidity, light and nutrient supply, thereby ensuring stable and optimized growing conditions. Despite its potential, gaps remain in terms of affordability, energy efficiency and accessibility for small-scale farmers, highlighting the need for continued innovation and scalable solutions in this field.

Key words: Controlled Agriculture Environment, vertical farming, Hydroponics, Climate control, Sustainable Agriculture.

Introduction

With the global population projected to reach 9.7 billion within the next 25 years, demand for food is set to rise dramatically. This growth requires food systems to increase production by more than 50% while addressing distribution inefficiencies to ensure food reaches where it is needed the most. Opportunities to expand agricultural land are limited and efforts to do so can be environmentally harmful. While productivity gains can be realised on existing farmland, the ability to cultivate crops and maximise yields on land that is not typically used for conventional agriculture will be essential for achieving long-term food security and environmental sustainability. Controlled Agriculture Environment (CAE) *i.e.*, greenhouses or vertical farms alongside a variety of enabling technologies to produce crops in nonconventional settings. CAE can reduce agricultural water usage by 53 to 98% and chemical usage by 100%, while using less land to produce the same amount of food as conventional farming. However, current CAE systems are often energy-intensive and costly to set up, which could limit their sustainability and accessibility, particularly in resource-constrained settings. Advances in technology may decrease costs, making CEA viable in a broader range of contexts.

What is CAE?

Controlled Agriculture Environment (CAE) is an advanced agricultural production system that employs engineered structures and integrated control technologies to regulate key abiotic

factors such as temperature, light intensity, humidity, carbon dioxide concentration and nutrient delivery within a closed or semi-closed environment, thereby enabling optimized plant physiological performance, enhanced productivity and consistent crop quality independent of external climatic variability.

Structural Systems of CAE

1. Greenhouse Structure

- Maintains controlled temperature and humidity
- Allows optimized sunlight transmission or integration of artificial lighting
- Protects crops from external weather, pests and contaminants
- Supports integration of systems like irrigation, ventilation and CO₂ enrichment.

2. Vertical Farming Systems

- Fully enclosed, multi-layered systems designed to maximize space efficiency
- Crops are grown on stacked racks supported by structural frameworks
- Equipped with LED lighting systems for uniform light distribution
- Include airflow systems (fans and ducts) for temperature and humidity control
- Use insulated environments to isolate crops from external conditions, enabling precise environmental regulation and high productivity.

3. Container Farming Structures: Container farming uses modified shipping containers with insulation, vertical grow racks, LED lighting, hydroponic systems and climate control units to create compact growing environments. These portable and efficient structures support urban and remote farming, though their production capacity is limited.

Core Components of Controlled Agriculture Environment

Climate Control Systems: Climate control systems regulate temperature, humidity, and air circulation to maintain stable growing conditions. Humidifiers, dehumidifiers, and CO₂ enrichment improve plant health by preventing stress, reducing disease, and enhancing photosynthesis for better yield.

Lighting Systems: CAE uses LED lighting, soilless nutrient systems, sensors and automation technologies to precisely control plant growth conditions like light, nutrients, and environment. Integration of smart control systems with well-designed structures improves efficiency, sustainability, and crop productivity through real-time monitoring and optimization.

Nutrient Delivery System: Soilless cultivation methods like hydroponics, aeroponics and aquaponics deliver nutrients directly to plant roots in controlled amounts for better efficiency. Automated fertigation and water recirculation systems ensure precise dosing, reduce waste, and improve sustainability

Sensing and Monitoring Technologies: Sensors monitor key parameters like temperature, humidity, light, pH, EC, and CO₂ to track environmental conditions and plant health in real time. Continuous data collection helps detect anomalies early, improving system performance, reducing risks, and boosting productivity.

Automation and Control Systems: Automation connects all CAE components using PLCs and microcontrollers that adjust environmental conditions based on sensor data. IoT enables remote control, while AI and ML improve efficiency by predicting plant needs and optimizing resource use.

Importance of CAE in Future Food Production

- **Ensures year-round food production:** CAE allows continuous crop cultivation throughout the year by eliminating dependence on seasonal and climatic variations. (Benke, *et.al.* 2021)
- **Maintains stable and reliable supply:** By controlling factors like temperature, humidity, and light, it ensures a consistent food supply even under unpredictable weather conditions.

- **Increases crop productivity and growth rate:** CAE systems provide ideal environmental conditions that promote faster plant growth and result in higher yields per unit area.
- **Maximizes space utilization and efficiency:** Techniques like vertical farming enable multiple layers of crops to be grown simultaneously, increasing overall production efficiency compared to traditional farming methods.
- **Ensures efficient use of water resources:** Advanced methods like hydroponics and aeroponics minimize water usage by recycling and reusing water within the system.

Limitations of Controlled Agriculture Environment

- **High capital requirement:** The initial setup cost of CAE systems is very high due to the need for specialized structures, advanced equipment, lighting systems, and automation technologies, making it less accessible for small-scale farmers.
- **Energy dependency:** CAE systems, especially indoor farms and plant factories, rely heavily on electricity for lighting, temperature control and ventilation, which increases operational costs and limits use in areas with unreliable power supply.
- **Limited crop diversity:** CAE is mainly suitable for high-value and short-duration crops such as leafy greens, herbs, and some fruits, while large-scale cultivation of staple crops like wheat, rice, and maize is not economically feasible.
- **Technical expertise requirement:** Operating CAE systems requires knowledge of advanced technologies such as sensors, climate control, nutrient management and automation, which may not be easily available to all farmers.
- **Risk of system failure:** Since CAE systems depend on continuous functioning of equipment, any failure in power supply, irrigation, or climate control can quickly damage or destroy crops.

Conclusion

Controlled Agriculture Environment (CAE) offers a highly efficient and sustainable approach to food production by enabling precise control over growing conditions, resulting in improved crop yield, quality and resource utilization. While challenges such as high initial costs and energy demands persist, advancements in automation, renewable energy integration and data-driven technologies are steadily enhancing its feasibility. Overall, CAE presents a promising solution for ensuring consistent and resilient agricultural production in the face of climate variability and increasing global food demand.

References

1. Benke, K. and Tomkins, B., Future food-production systems: Vertical farming and controlled-environment agriculture. *Renewable and Sustainable Energy Reviews*, **141**: 11078
2. Dsouza, A., Newman, L., Graham, T. and Fraser, E.D., 2023. Exploring the landscape of controlled environment agriculture research: A systematic scoping review of trends and topics. *Agricultural Systems*, *209*, p.103673.
3. Dsouza A, Newman L, Graham T, Fraser ED. Exploring the landscape of controlled environment agriculture research: A systematic scoping review of trends and topics. *Agricultural Systems*. 2023 Jun 1; 209:103673.