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STRUCTURAL SYSTEMS IN CONTROLLED ENVIRONMENT AGRICULTURE

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Abstract. *Controlled Environment Agriculture (CEA) has emerged as an innovative approach to sustainable food production by providing precise control over environmental conditions, enabling year-round crop cultivation regardless of external climate. This review aims to evaluate the major structural systems used in modern CEA, including greenhouses, indoor vertical farms, modular container farms, and underground farming facilities. The study was conducted through a comprehensive review of scientific literature published between 2004 and 2025, with emphasis on the structural characteristics, operational performance, advantages, and limitations of each system. The analysis indicates that each structural system offers distinct benefits depending on production objectives, climatic conditions, and resource availability. Greenhouses provide cost-effective production through natural sunlight, while indoor vertical farms achieve high productivity through intensive environmental control. Container farms offer flexibility and localized food production, whereas underground farming presents opportunities for utilizing existing infrastructure with improved environmental stability. The review concludes that no single structural system is universally optimal; instead, selecting an appropriate CEA structure should depend on local environmental, economic, and technological conditions. Integrating these systems into sustainable urban agriculture can contribute significantly to future food security and climate resilience.*

Keywords: *Controlled Environment Agriculture, CEA, greenhouse, vertical farming, container farming, underground farming, urban agriculture, structural systems, sustainable agriculture, food security.*

Annotatsiya. *Nazorat qilinadigan muhit qishloq xo'jaligi (Controlled Environment Agriculture – CEA) tashqi iqlim sharoitidan qat'i nazar yil davomida qishloq xo'jaligi mahsulotlarini yetishtirish imkonini beruvchi zamonaviy texnologik yondashuv hisoblanadi. Mazkur maqolaning maqsadi CEA tizimlarida qo'llaniladigan asosiy konstruktiv yechimlar, jumladan issiqxonalar, yopiq vertikal fermalar, konteyner fermalari va yer osti fermalarining tuzilishi, ishlash xususiyatlari, afzalliklari hamda cheklovlarini tahlil qilishdan iborat. Tadqiqot 2004–2025-yillarda chop etilgan ilmiy adabiyotlarni tahlil qilish asosida amalga oshirildi. Tahlil natijalari shuni ko'rsatdiki, har bir konstruktiv tizim ishlab chiqarish maqsadi, iqlim sharoiti va mavjud resurslarga qarab o'ziga xos ustunliklarga ega. Issiqxonalar tabiiy yorug'lik hisobiga energiya sarfini kamaytirsa, vertikal fermalar sun'iy boshqariladigan muhitda yuqori hosildorlikni ta'minlaydi. Konteyner fermalari moslashuvchan va*

mahalliy oziq-ovqat ishlab chiqarishga qulay bo'lsa, yer osti fermalari mavjud infratuzilmadan samarali foydalanish imkonini beradi. Xulosa qilib aytganda, barcha sharoitlar uchun yagona ideal konstruktiv tizim mavjud emas. Eng maqbul CEA tizimini tanlash mahalliy ekologik, iqtisodiy va texnologik omillarga asoslanishi lozim. Ushbu tizimlarning uyg'un qo'llanilishi barqaror shahar qishloq xo'jaligi va oziq-ovqat xavfsizligini ta'minlashga xizmat qiladi.

Kalit so'zlar: *Nazorat qilinadigan muhit qishloq xo'jaligi, CEA, issiqxona, vertikal ferma, konteyner ferma, yer osti fermasi, shahar qishloq xo'jaligi, konstruktiv tizimlar, barqaror qishloq xo'jaligi, oziq-ovqat xavfsizligi.*

Аннотация. *Сельское хозяйство с контролируемой средой (Controlled Environment Agriculture, CEA) представляет собой современный подход к производству сельскохозяйственной продукции, обеспечивающий круглогодичное выращивание культур независимо от внешних климатических условий. Цель данной статьи заключается в сравнительном анализе основных конструктивных систем, применяемых в современных CEA, включая теплицы, вертикальные фермы, контейнерные фермы и подземные фермы. Исследование выполнено на основе анализа научных публикаций, опубликованных в период с 2004 по 2025 год, с акцентом на конструктивные особенности, эксплуатационные характеристики, преимущества и ограничения каждой системы. Результаты обзора показывают, что каждая конструктивная система обладает своими преимуществами в зависимости от целей производства, климатических условий и доступности ресурсов. Теплицы обеспечивают экономичное производство благодаря использованию естественного освещения, вертикальные фермы позволяют добиться высокой продуктивности за счёт полного контроля условий выращивания, контейнерные фермы отличаются мобильностью и возможностью локального производства, а подземные фермы эффективно используют существующую инфраструктуру и обеспечивают стабильный микроклимат. Сделан вывод о том, что универсальной конструктивной системы для всех условий не существует. Выбор оптимального решения должен учитывать местные экологические, экономические и технологические особенности. Комплексное использование различных CEA-систем может способствовать развитию устойчивого городского сельского хозяйства и укреплению продовольственной безопасности.*

Ключевые слова: *сельское хозяйство с контролируемой средой, CEA, теплица, вертикальная ферма, контейнерная ферма, подземная ферма, городское сельское хозяйство, конструктивные системы, устойчивое сельское хозяйство, продовольственная безопасность.*

INTRODUCTION

CEA is an acronym for Controlled Environment Agriculture. CEA is a crop production system that is separated from outside environment and has regulated environmental conditions including light, temperature, humidity, and carbon dioxide. CEA systems allow year-round production in almost every climate, weather it is arid, polar, or densely populated city (McCartney & Lefsrud, 2018). Even in urban regions, structural systems are able to support food production in warehouses, high-rise

buildings, rooftops, and underground spaces. This report critically discusses different structural systems in modern CEA, analysing their types, materials, advantages, and limitations.

LITERATURE REVIEW

Structural systems are backbones of Controlled Environment Agriculture. They are engineered frameworks that support artificial environment. Their design determines resource efficiency, and the adaptability of crops (McCartney & Lefsrud, 2018).

Greenhouses are ethe prominent and widely known type of CEA because it is one of the most widely utilised structures (Fadel et al., 2016). Ther are less known yet more advanced CEA systems including indoor vertical farming, which rely on multilayer growing racks and LED lighting. This kind of systems are popular in urban areas because of their ability to maximise vertical space (Kabir et al., 2023).

Other structural systems include growth chambers, which are popular with precise and isolated environments for research (Thiel et al., 1996), and modular container farms offering portable units (Song et al., 2023). Finally, there are underground farms.

RESEARCH METHODOLOGY

This study employed a qualitative literature review methodology to examine structural systems used in Controlled Environment Agriculture (CEA). Relevant scientific publications were collected from internationally recognized databases, including Google Scholar, Scopus, Web of Science, SpringerLink, and ScienceDirect. The reviewed literature primarily consisted of peer-reviewed journal articles published between 2004 and 2025, with emphasis on studies investigating greenhouse structures, indoor vertical farming, modular container farms, and underground farming systems.
The collected publications were screened based on their relevance to structural design, operational performance, resource efficiency, environmental control, and sustainability. A comparative analytical approach was used to evaluate the structural characteristics, advantages, limitations, and practical applications of each CEA system. The findings were synthesized using descriptive and comparative methods to identify the strengths and weaknesses of different structural systems and their potential contribution to sustainable urban agriculture.

ANALYSIS AND RESULTS.

1. Greenhouse Structures

Overview. Greenhouses consist of a metal frame (often steel or aluminium) covered with transparent or translucent cladding materials. Types of materials used in greenhouse coverage strongly influence light transmission and heat flow into the growing space. Those materials include glass, polyethylene, and polycarbonate, (Fadel et al., 2016). Some research shows that there would be up to 50% change in internal temperature with certain polycarbonate combinations (Fadel et al., 2016). Frames, foundations, cladding, and ventilation must withstand wind and structural loads as well as enabling effective light entry and climate control (Dalai et al., 2020; Waaijenberg, 2004).

Operational performance. Greenhouses combine solar gain with mechanical controls (fans, shading, cooling pads). Coverings regulate heat and light but, without ventilation, temperatures can be as high as 45°C (Fadel et al., 2016). properly ventilated and insulated greenhouses can sustain relatively stable microclimates, but controlled climate is highly sensitive to external weather and the quality of structural design (Waaijenberg, 2004).

Benefits and limitations.

Greenhouses offer lower capital cost per area and rely on natural light which reduces energy use. However, they are sensitive to availability of the sun and weather conditions, and cooling loads. poor design may lead to overheating or low light eventually reduced yields (Fadel et al., 2016; Dalai et al., 2020).

Picture 1. Greenhouses

a) types of greenhouse b) industrial greenhouses in Netherlands

2. Indoor Vertical Farming Facilities

Overview. Indoor vertical farms are distinguished by fully enclosed structures, where crops are grown on stacked racks. One key difference between greenhouses and indoor farming is exposure to the sun: greenhouses have access to sunlight whereas indoor farms have to rely on artificial led lights. Structural systems consisted of multi-tiered shelving, irrigation pipes, and LEDs (Kabir et al., 2023).

Operational performance. Vertical farms allow high level of climate control. lighting, and nutrient delivery, CO^2 concentrations are adjustable to maximize productivity year-round. Thanks to the advancements in sensors, automation, and environmental control, operational reliability and crop uniformity is being improved (Kabir et al., 2023). Recent work on indoor agriculture mentions the need for more

research on integrating crop cycles with energy-management to optimise the system (Wang et al., 2025).

Benefits and limitations. Extremely high yield per unit ground area is the key benefit of vertical farms. The ability to locate production in the city area is another advantage to consider. In today's global food systems agricultural products travel thousands of kilometres to get to the consumers which increases the cost of the product and contributes to the climate change. Vertical farms can solve this very problem by lowering food miles (Kalantari et al., 2017). Yet, economically vertical farms can not compete in the market because of its high initial investment and high labour, energy costs (Moghimi & Asiabanpour, 2023).

Picture 2. Example of vertical farming facility
Retrieved from: https://share.google/laSVPfap2xO19AgDP

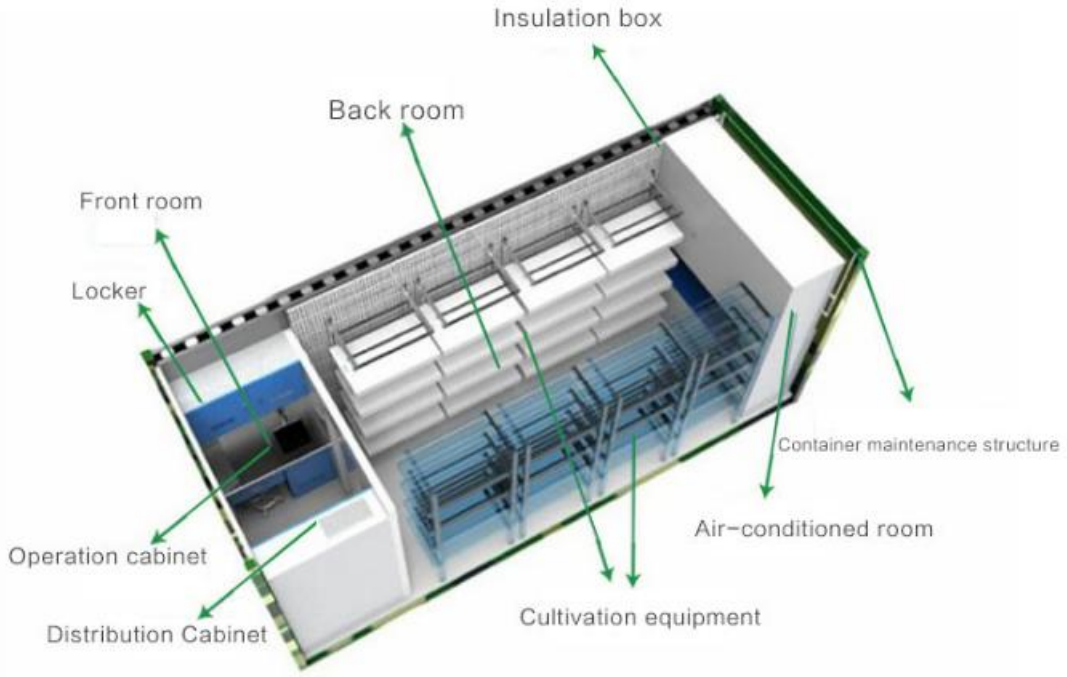
3. Modular Container Farms

Overview. Modular CEA systems in shipping containers or similar structures are called Container farms. What set them apart is their walls and roof which are covered with insulation and integrated HVAC systems. Similar to vertical farms the interior can be equipped with multi-layer growing racks and LED lighting (Song et al., 2023).

Operational performance. Energy modelling studies shows that container farms can support ideal growing conditions, but they have a tendency to have high energy demand, especially in warmer regions (Song et al., 2023). Thanks to their compact and uniform design they are ideal to conduct research on different plant varsities.

Benefits and limitations. Portability, rapid deployment, and standardisation are the main benefits of container farms. The location of placement can vary widely from parking lots, vacant plots, to next to distribution centres which provides extra localised production. Regarding the structural viewpoint, their unique design allows avoiding

complex building integration. However, because of their limited internal volume total output is much less compared to other CEA structures, (Song et al., 2023).



Picture 3. Structure of Container farm
Retrieved from: https://www.omana.cn/en/product/product-90-923.html

4. Underground Farming Structures

Overview. Underground farming is relatively new frontier in CEA which makes use of subsurface spaces for example abandoned mines, tunnels, car parks, or other underground spaces. However, new cavities would also be created (Langefeld & Tegtmeier, 2019). In underground farming structures the main structural task is retrofitting these spaces with internal frames for growing racks, lighting, and irrigation, along with ventilation. The rock or concrete surrounding the structure provides structural strength and insulation, similar in function to the envelope of other CEA facilities (McCartney & Lefsrud, 2018; Langefeld & Tegtmeier, 2019).

Operational performance. Subsurface environments usually have relatively stable temperatures which eliminates the need for energy intensive climate control systems. on top of that, this type of environments protects the farm from external weather (Langefeld & Tegtmeier, 2019). HVAC and control systems are utilized to control the micro-climate within underground farms, comparable to those in other indoor farms.

Benefits and limitations. There are several advantages of underground farms a major one is being the reutilization of existing infrastructure (Langefeld & Tegtmeier, 2019). The external weather patterns such as thermal changes and precipitation is physically blocked which can enhance resilience in extreme climates (McCartney & Lefsrud, 2018). On the other hand there are some limitations that worth mentioning including significant retrofit costs for ventilation, safety, LED lights and limited

real-world experience, since relatively few underground facilities has been built (Langefeld & Tegtmeier, 2019).

Picture 4. Structure of Underground farms

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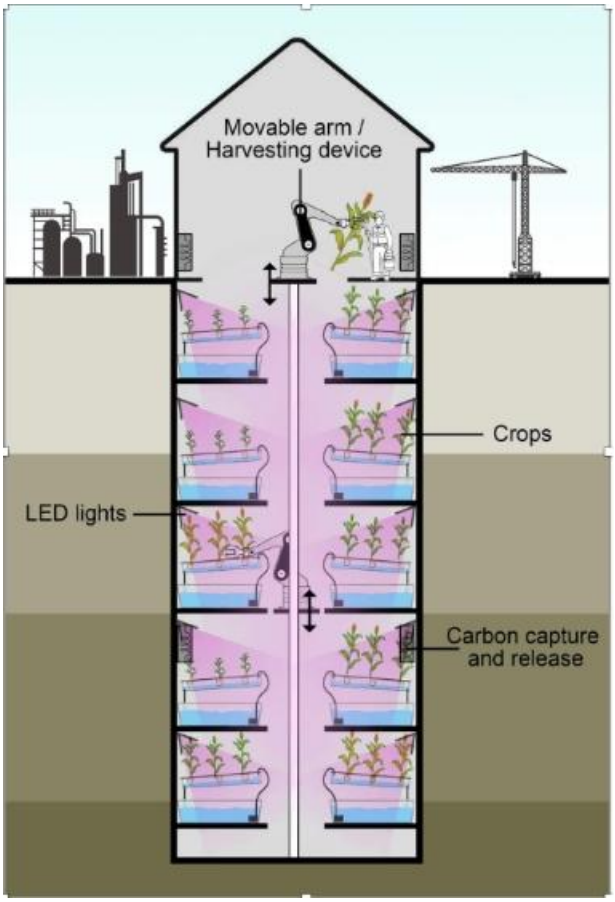

CONCLUSION

Structural systems build the essential foundation of contemporary Controlled Environment Agriculture (CEA). The analysis of four key structure types—greenhouses, vertical farming facilities, container farms, and underground farms—shows how each system offers specific advantages, operational differences, and unique limitations. Greenhouses are the most efficient structures, because they benefit from natural illumination yet they are the most sensitive to external weather. Vertical farms, in contrast, fully enclosed and that enable high-density production but economic contains remains to be the biggest challenge. Creating decentralised urban production is the main advantage of container farms. Moreover, they introduce a flexible, modular approach, though governments can not provide enough calories with container farms because they are small and energy intensive. Another unique CEA system is underground farms which repurpose subsurface infrastructure already in place. However just like vertical farms underground farm's initial investment and operational costs comes with a high price tag attached. As discussed in this report, no Controlled Environment Agriculture (CEA) system can feed the entire city. However, when applied in harmony and deployed according to suitable conditions, these systems can build sustainable urban agriculture.

Based on the reviewed literature, several recommendations can be proposed for improving the implementation of Controlled Environment Agriculture systems. Select CEA structural systems according to local climatic conditions, economic capacity, and

production objectives rather than applying a single approach in all situations. Increase investment in energy-efficient technologies, including advanced LED lighting, renewable energy systems, and automated environmental control, to improve the economic sustainability of indoor farming.

Encourage the integration of Controlled Environment Agriculture into urban planning by utilizing rooftops, vacant buildings, shipping containers, and underground spaces for local food production. Promote interdisciplinary collaboration among engineers, agronomists, architects, and policymakers to design more efficient and resilient CEA facilities. Support further research on reducing energy consumption, optimizing structural design, and improving the long-term economic feasibility of vertical and underground farming systems. Develop government policies and financial incentives that encourage investment in sustainable Controlled Environment Agriculture technologies and strengthen urban food security.

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