Controlled Environment Agriculture and Sustainability

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Controlled Environment Agriculture (CEA) is one of the emerging agri-food technologies that has increasingly gained attention from researchers, practitioners, and consumers for its potential to make growing practices more sustainable. The term controlled environment agriculture was first introduced in the 1960s, referring to an intensive approach for controlling plant growth through the broad implementation of advanced techniques and innovations in technology. In this sense, CEA is not a completely new concept, as agriculture has witnessed a technological and functional evolution over the last century, from simple row covers in open fields to highly sophisticated indoor facilities where all growing elements are under accurate control. By controlling the growth environments and manipulating plant responses to their environments, CEA claims to offer advantages to increase production efficiency, optimise plant yield, and improve product quality.

Keywords: sustainability framing ; controlled environment agriculture ; consumer perception

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1. Environmental Sustainability of Controlled Environment Agriculture

There are supposed to be multiple environmental benefits associated with the features of CEA growing systems, including more efficient land and water use, less input of fertilisers and sprays, and smaller carbon footprints for transportation, etc. [1]. Different from conventional outdoor farming systems and greenhouse production systems, where arable lands are occupied for single-layer crop production, CEA typically features indoor farms based on a high-rise factory design with crops growing in stacked layers, usually on soilless nutrition-dense solutions. This means CEA requires less land use for the same amount of crop production. Hydroponics and aeroponics are commonly adopted within CEA, thus water is more precisely applied and the nutrient solution can be easily recycled in a closed-loop [2]. Some research suggests that CEA can save up to 90% of water use compared with conventional greenhouses and up to 99% compared with open field growing [3]. Another major benefit of CEA is that the growing systems are “closed” indoor operations, which means the crops will be less exposed to the spread of pests and adversary weather conditions. This will help significantly reduce the need for pesticides and other sprays compared with outdoor farming practices, thus pollution of the soil and water by pesticides will also be much lower [1][4][5].

The carbon footprint of food supply chain is another major consideration for a sustainable growing system. CEA systems are typically implemented within or close to urban areas, resulting in a much shorter distance between the production location and the suppliers/consumers, therefore significantly lowering the food miles and use of fossil fuel in transportation [1][4][5]. Furthermore, CEA can operate all year round to supply stable fresh produce according to the demand, thus there would be minimal GHG for storage and less food loss and wastage during transportation and storage [2].

Despite all these potential benefits, CEA may still cause negative impacts on the environment. Another major feature of CEA is that these systems usually operate 24h per day with temperature fully controlled, and using artificial lights instead of natural sunlight. A considerably higher amount of electricity will be needed to artificially maintain the optimal growing conditions for crops across different seasons all year round, and thus contributes to significant energy use and GHG emission [3][6][7]. Advancement in renewable energy technology and its implementation is crucial to address this concern to strengthen the sustainable image of CEA [8]. In addition, CEA operates in concealed buildings, and the construction of these buildings represents a considerable source of carbon emission [9]. To reduce the environmental impact of CEA from this perspective, some vertical farms were built using abandoned or re-purposed buildings to avoid carbon emissions resulting from newly constructed buildings [1][10]. A recent case study accessing the life cycle of different types of farms in the Nertherlands based on building footprint suggests that conventional greenhouse structure emits 2.7 times more CO^2 equivalent than a vertical farm using existing buildings [11].

2. Economic Sustainability of CEA

Economic feasibility and profitability are vital for the CEA sector to survive and thrive in competition with conventional farming methods. Theoretically, CEA systems hold multiple economic benefits that are mainly related to enhanced productivity and efficiency. Operating indoor on a 24h basis and being protected from loss from external weather conditions such as floods, droughts, and sun damage, CEA systems are capable of securing stable high yield all year round with consistent quality. Some research reported up to 100 times higher yield in CEA compared with conventional farming [1]. There is also supposedly a lower cost for the input of fertilisers, herbicides, and pesticides, as demand for them is largely reduced in CEA systems. Additionally, when CEA systems are located close to the market and end consumers, storage and transportation cost for CEA will also be minimised [1][4][5].

While many of these economic advantages seem to be promising for CEA systems, there are many challenges acknowledged as well. Start-up costs and capital investments to set up new CEA systems are deemed to be very expensive, and maintaining the continuous operation of CEA with artificial lights as well as maintaining control of other growing elements will inevitably result in continuous and enormous energy costs [1][4][5]. Being located in or close to urban areas also means expensive land and infrastructure cost [1]. Moreover, apart from leafy greens and herbs, currently there is a lack of economically viable variety of crops that are suitable for CEA, which further limits the economic feasibility of CEA systems [2][5]. Despite all these challenges, Avgoustaki and Xydis demonstrated that vertical farms can be more profitable for investors, saving significant resources compared with conventional greenhouses, according to the internal rate of return and the net present value indexes [12].

As an emerging industry, research in the CEA sector has been largely driven by economic factors such as productivity, energy use, and staff requirements, in order to minimise input and optimise production value. It is criticised that many environmental benefits of CEA, e.g., improved land- and water-use-efficiency and lower GHG emissions, are largely achieved as an outcome of cost-saving rather than deliberate efforts to improve environmental sustainability [2].

Overall, the optimal production output/value and minimal environmental input/impact through enhanced productivity and efficient use of resources is the main narrative that reflects both the environmental and economic aspects of CEA as a sustainable model of food production. To achieve economic sustainability for commercial CEA operations, current research suggests careful consideration of capital investment and ongoing operating costs, production volume, product quality and consistency, and local market trends [13]. Little has been discussed in the literature regarding how CEA would impact the economic sustainability of the entire horticulture sector, and the overall economic development.

3. Social and Cultural Sustainability of CEA

Food security and accessibility are the key themes relevant to social sustainability concerning CEA given its potential high-yield and local production features [14]. Several studies demonstrated how CEA could improve food security and food accessibility in some countries where resources are limited for agriculture and food production. For example, Mok et al. highlighted how vertical farming, together with aquaponics and other novel technologies, have been adopted in Singapore to enhance self-production of food [15]. Although very inspiring, the authors also admitted that many of these implementations are still relatively nascent, and there are numerous challenges to be addressed before these technologies can be widely accepted and implemented. Likewise, Sumanta and colleagues discussed how vertical farming has become increasingly used in India since 2019 as a way to increase food production and eradicate poverty in the country [16]. Pulighe and Lupia further highlighted the important role of innovative growing systems such as CEA in lessening uncertainties from global systemic risks such as the COVID-19 Pandemic [17]. Scholars also pointed out that less developed countries and regions that could benefit the most from CEA in solving food security may also not be able to afford CEA, thus will compromise the potential of CEA contributing to the sustainable development goals of zero hunger and nutrition equity [2][5].

Advocates of CEA also claim other promising social advantages that CEA could offer, such as creating new jobs in related sectors and regions, improving discretionary income because of potentially lower food costs, and addressing isolation in remote rural communities [1][4][18]. The disruption of CEA to traditional farming was also considered in the transitioning process to CEA operation [1]. It is also anticipated by some scholars that vertical farming may have the potential to reinforce social interactions within the facility and improve overall working conditions for workers along the supply chain [18]. However, these social implications are more difficult to quantify compared with evaluating environmental impacts such as GHG emissions, and there is currently no consistent measurement to reflect the potential social impact of CEA [19]. Furthermore, when the social impact of CEA was discussed, such discussion was usually not under a sustainability framework and thus has not been discussed in relation to its connection to the other two dimensions of sustainability.

Compared with the environmental and economic benefits, the social effects of CEA have been discussed and evaluated less often, and the cultural perspective of sustainability relating to CEA is barely discussed at all. Some scholars have raised the need to develop more people-oriented principles to guide responsible socio-technical transitions in the agriculture sector, by factoring in both the positive and negative implications of agricultural technology innovations [20]. As a consequence, it is suggested that policymakers should take a proactive approach and invest in education and infrastructure development to ensure a smooth transition to wider implementation and adoption of CEA in society [1].

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