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Review

Sustainability Framing of Controlled Environment Agriculture and Consumer Perceptions: A Review

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Abstract: The ongoing criticism of conventional agricultural activities being unsustainable in the face of climate change and global population growth has been one of the key drivers for technological innovation in this space. Controlled Environment Agriculture (CEA), especially in the high-tech form of vertical farming, as a new agri-food technology, has been positioned as a sustainable solution to the dilemma of feeding the world and preserving the planet. Acknowledging sustainability as a multi-dimensional concept encompassing environmental, economic, social, and cultural aspects, this review briefly outlines the evolving meaning of sustainability, and how CEA has been framed as sustainable in the literature. Specifically, the review examines studies that have investigated consumer perceptions and acceptance of CEA and discussed how sustainability features of CEA were presented to consumers in a diverse way across these studies. The review highlights that the social and cultural dimensions of sustainability were largely neglected not only in research that focused on the development of CEA, but also in the exploration of consumers' perceptions of CEA. A more holistic examination of the sustainability of CEA and a comprehensive understanding from consumers is important for transitioning towards more sustainable production systems enabled by new technologies such as CEA.

Keywords: sustainability framing; controlled environment agriculture; consumer perception

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1. Introduction

Human impact on the planet, particularly the impact of agricultural activities on the environment, is a major concern for the sustainable future of human beings and the planet [1]. The sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC) acknowledges with high confidence that increased atmospheric temperature, drought frequency, rates of tropical and extratropical cyclones, and increased soil moisture deficits are a result of human influence [2]. Farming and growing practices, among other human activities, have been identified as core drivers of climate change and environmental degradation [3–5]. Research points out that human activities directly associated with agriculture, including land-use change, food waste, and supply chain, contribute 21–37% of all greenhouse gas (GHG) emissions each year [2]. According to the Food and Agriculture Organization of the United Nations (FAO), the global food system accounts for 38% of global land surface cover, of which one-third is used as cropland [6]. Additionally, agriculture accounts for approximately 70% of global freshwater withdrawals globally, on top of water consumption after rainfall and evapotranspiration [7].

It is predicted that the increased presence of extreme hydro-meteorological events (e.g., droughts and floods) will further deteriorate the growing conditions for crops, and the expansion and intensification of conventional farming practices in order meet the global food demand may result in severe detrimental environmental consequences (e.g., loss of biodiversity, deforestation, poor air and water quality) [8,9].

Adding more to the existing pressure on the environment, the global population has just reached 8 billion on 15 November 2022 [10], and is anticipated to continually grow to reach 9.7 billion by 2050 [11]. The growing global population and increased demand for food, especially healthy and nutritious food, has heightened the need for more sustainable methods of food production. Securing food for the growing population whilst reducing environmental impacts has become a fundamental theme driving agri-food technology innovation [12]. Novel agri-food technologies have been positioned as a promising solution providing highly optimised and efficient methods of production that minimise the environmental impacts of agriculture [13]. These technologies include Controlled Environment Agriculture (CEA) [14], Cellular Agriculture (CellAg) [15], Nanotechnology for agricultural control [16], and so on.

CEA is one of these new agri-food technologies that has increasingly gained attention from researchers, practitioners, and consumers. 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 [17]. 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 [18]. 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 [14,19–22].

Over the past decade, CEA, typically in the high-tech form of vertical farms or plant factories, has been increasingly considered as a sustainable method of intensive food production [14,23]. This form of CEA typically features indoor farms operating in a continuous 24/7 manner based on a high-rise factory design with crops growing in stacked layers, using soilless nutrient-dense substrates and artificial LED lights instead of natural sunlight, and having accurate control of other growing elements including temperature, humidity, amount of water and other nutrients needed, etc. [14]. For example, AeroFarms in Newmark, United States, is amongst one of the earliest vertical farms in the world (Figure 1) to supply produce to mainstream retailers including Walmart [24]. In some countries and regions, such as America, Canada, and Japan, CEA has been playing an increasingly important role in the commercial production of ornamental plants, vegetable crops, and young plant material from seed, cuttings, or tissue-culture [25,26]. In addition to the large-scale commercial CEA operations in the forms of vertical farms and plant factories, there have also been small-scale in-home CEA production systems and in-store CEA systems suitable for supermarkets setting [27,28]. Given the global mission of "feeding the world" and its requirement for large-scale production, in this review we will focus on the large-scale operation of CEA only—which are the multiple-story indoor vertical farms that supply produce to retail channels.

Figure 1. Indoor Vertical Farm.

Sustainability is crucial for the positioning of CEA to gain social and cultural licenses to operate in the society, and ultimately to be adopted by end consumers. Despite the fast development of CEA and the global attention it has gained over the past decade, understanding of consumer perceptions, attitudes, and acceptance of CEA and its production is still limited and insufficient [29]. Furthermore, sustainability has been recognised as a multi-dimensional concept encompassing environmental, economic, and social aspects [30]. Although there is a growing body of consumer insights in the literature concerning CEA, the majority of work has only addressed the sustainability of CEA from the environmental perspective. To date, no specific work has been done to understand how consumers perceive the different dimensions of sustainability of CEA from a holistic approach, and how these perceptions may impact consumers' acceptance of CEA and its production. Previous studies have heightened that acceptance of a new agri-food technologies are closely related to the nature of the technology, as well as the social-cultural system it is introduced to [31–33]. Neglecting the social and cultural impacts is not only misaligning with the integrated spirit of sustainability, but also might lead to the risk of rejection by consumers due to social-cultural concerns. Thus, understanding consumers' perceived sustainability of CEA from not only environmental but also economic, social, and cultural dimensions is crucial to facilitate the obtaining of social and cultural licenses to operate for CEA, and ultimately promote acceptance from end consumers.

To fill this gap, this review revisited the origins and evolution of sustainability as a holistic concept, and analysed the posited understanding of sustainability as it relates to CEA, in particular how different dimensions of sustainability were reflected in the advancement of CEA over time. Specifically, we reviewed consumer responses to CEA in the literature with particular attention on how CEA was framed and presented to, and perceived by, consumers in these studies. The purpose to review consumer perceptions is to examine whether some dimensions of sustainability were communicated to consumers disproportionately, and how perceived sustainability affects consumer acceptance of CEA. A conclusion and suggestions for future research are provided at the end of this review.

2. Methodology

Three domains were reviewed in the current work, namely, sustainability as a holistic concept with multiple dimensions, CEA as a sustainable technology, and consumer perception of CEA and its sustainability. The review of sustainability concept was to establish a holistic framework of sustainability which then can be applied to the analysis of how CEA was positioned as sustainable, and how consumers perceived CEA as sustainable or not.

As a starting point, the electronic academic database "Web of Science" was consulted using different combination of key words for each domain, respectively in the Abstract Field (Table 1). No specific timefreame was applied in the search.

Table 1. Review Methodology.

Review Domain	**Search Strategy**			**Article Number**
	Key Word 1	**Key Word 2**	**Key Word 3**	
Sustainbility as a holistic concept	"sustainability" or "sustainable development"	"three-pillar"		49
CEA as a sustainable technology	"Controlled environment agriculture" or "Vertical Farm*" or "indoor farm*" or "Indoor Growing" or "Plant Factor*"	"Sustainab*"		189
Consumer perception of CEA and its sustainability	"Controlled environment agriculture" or "Vertical Farm *" or "indoor farm*" or "Indoor Growing" or "Plant Factor*"	"Sustainab*"	"consum*" or "willingness to pay" or "attitude*" or "accept*" or "perception*"	108

The initial "Web of Science" search collected 49, 189, and 108 articles for each domain, respectively from the literature. In the next step, all abstracts were read through by the researchers to determine on each article's relevance to the domains under review before a full review of that article. For the review of CEA as a sustainable technology, articles focused on technical details were not included. For the review of consumer perceptions, non-emprical articles were not included, so as articles which did not measure consumer perceptions of CEA. In the final step, Google Scholar was also consulted as a complementary source of additional articles where necessary.

3. Sustainability and Its Various Dimensions

Sustainability is a concept that has been broadly used across different disciplines and contexts, which has contributed to its ambiguity in conceptualisation, and led to the formation of various definitions and interpretations in the literature over time [34]. With no intention to be exhaustive, here we briefly outline the origins of the concept of sustainability, how it evolved in complexity over time, and the commonly used interpretations of sustainability today, in particular the widely adopted three-pillar approach of sustainability.

3.1. Origins of Sustainability

The origins of the concept of sustainability are far from straightforward. The earliest conceptions of sustainability were first documented within the 17th century German forestry industry—in theory the number of trees cut down for use should not exceed a forests' ability to regrow, ensuring future use of the forest [35,36]. This concept, similar to the modern concept of a maximum sustainable yield, was established to prevent over-harvesting. Following the Industrial Revolution which brought fast economic growth and material advancement, concerns with population growth and the increase in consumption, eco-scarcity, and humans depleting the environment's natural resources became prevalent [34]. After a period of unprecedented economic prosperity post World War II, people became more aware of the threats that human activities posed to the environment and the survival of humans, and environmentalism started to receive more public attention [34].

The role of sustainability in modern-day environmentalism began to take form in the mid-twentieth century [37], following a series of highly publicised environmental matters which formed what was described as the 'environmental crisis'. Ecologists began to question the environmental consequences brought about by the Industrial Revolution, in particular relating to the extraction of finite resources, the consequences of man-made chemicals on ecosystems, and the implications for the future [38]. Under the conflicting ideas of conservation which focused on the protection of natural resources, and development which implied the exploitation of resources, the concept of sustainable development emerged in the early 1970s as a compromise to achieve a balance between conservation and development [34]. Governing bodies such as the International Union for Conservation of Nature (IUCN) and the United Nations (UN) became a central part of global environmental governance. The 1972 UN Conference on the Human Environment was the first conference that placed environmental degradation as a major issue for humanity, and developed a connection between the development of countries, economic growth, and anthropogenic pollution in the world [39]. This conference instilled early conceptual elements of modern sustainability, suggesting that development should harmonise social and economic objectives alongside environmentally sound management [30].

'Sustainable Development' became a popularised term following the 1987 Brundtland Report *Our Common Future* by the World Commission on the Environment and Development (WCED). The Brundtland Report defined sustainable development as "the ability to meet the needs of the present without compromising the ability of future generations to meet their own needs" [40]. While the literature has identified a distinction between the concepts of sustainable development and sustainability, the two have become synonymous with one another in many contexts. Development (ranging from technological to economic) has become an implicit part of sustainability, both share fundamental similarities which have the common goal of addressing human impact on the world [30,41].

3.2. The Three-Pillar Conceptualisation of Sustainability

Sustainability has become well-known as encompassing three interconnected systems of society, namely, the environmental, the social, and the economic, following the 2002 World Summit on Sustainable Development [41]. The implication is that each system has an impact on the other two, and that the balanced integration between each of the three will deliver sustainable outcomes [42]. There are a few things to note with this 'three-pillar' approach of sustainability. First, the use of 'dimensions' is arbitrary: across literature terms such as 'pillars', 'systems', and 'components' have been used by different scholars to describe the three focal points [30,36]. Second, the terms 'environmental' and 'ecological' are used interchangeably across the literature, both encompassing the same aspects. Lastly, and in a similar vein, the literature agrees that sustainability as a three-dimensional approach does not have a theoretical foundation despite being the most "common sense" view of sustainability, implemented across multiple areas of policy [30,41].

3.2.1. Environmental Sustainability

Life on Earth relies on natural resources and the functioning of the ecosystem. The environmental dimension of sustainability is built on the earliest conception of sustainability, specifically the appropriate use of resources for current and future generations. Black describes environmental sustainability as "the extent to which ecological systems . . . are capable of continuing to perform their essential functions into the future" (p. 34). Subsequent definitions of sustainability share similar themes: Geissdoerfer et al. describe environmental sustainability as a situation where human activity is conducted to conserve functions of the Earth's ecosystem [36]; Moldan et al. suggest that pathways towards environmental sustainability means a transformation of lifestyle to support security by maintaining the supply of goods and services, and an attempt to improve human welfare by protecting the sources of raw materials [41].

Sustainable development is concerned with achieving global equity for the current and future generations with regard to the distribution of natural resources. Environmental sustainability prioritises ecosystem services, the beneficial functions that the biophysical system provides to humans. This includes provisionary services such as food and water; regulation services to regulate the climate, water quality and disease; and cultural services that provide recreational and aesthetic value [43]. Living within the limits of ecosystem services in the pursuit of preserving them is seen as the basis of the environmental dimension of sustainability [41]. It is no doubt that environmental sustainability is a most addressed dimension of sustainability and is most broadly recognised by the public.

3.2.2. Economic Sustainability

Economic growth is the foundation for a society to survive and thrive, and to provide goods and services to meet human needs. As some scholars have pointed out, the concept of sustainable development is a compromise between growth and conservation, and is positively inclined towards the growth and modernization viewpoints, indicating stronger anthropocentric views than eccentric views [34]. From a more economic point of view, Conway defines sustainability as "the ability of a system to maintain productivity in spite of a major disturbance" [44] (p. 35). In a similar sense, Black describes economic sustainability as "to do with the extent to which economic systems are capable of continuing for the long term" [42] (p. 34). These definitions imply that economic sustainability focuses on the ability of production systems to provide goods and services, the adaptability of economic systems to different environmental conditions, and maintaining social and cultural aspects of a community [42].

Criticism of the economic status quo, including the blind pursuit of economic growth, short-sighted profit-driven agriculture, or industrialism without care for the fragile and complex ecosystems, is one of the cornerstones on which the sustainability concept is based [30]. Long-term and reasonable economic development and growth under the constraints of finite resources is the key connotation of sustainability in this regard, implying that current economic activities should not cause an excessive burden on future generations [45]. Thus, environmentally friendly and resource-saving technologies have become a key concept of a green economy, an economy that "results in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities" [46] (p. 2), according to the United Nations Environment Programme (UNEP).

In the business context, in 1997, Elkington introduced the triple bottom-line framework, which further breaks down into three tenets of people, planet, and profit, suggesting it is essential for businesses to make decisions not only on economic returns but also on environmental protection and social justice [47].

3.2.3. Social Sustainability

The social perspective is a very broad yet insufficiently understood dimension of sustainability. It diverts from the tangible methods of value that environmental and economic perspectives tend to adopt, and addresses the need for equity within and between generations, and within and between diverse ethnic and social groups [34]. The representation of this perspective therefore calls attention to the social structures of a community and how they can support current and future generations.

Despite the lack of clear definitions as to what social sustainability consists of, approaches toward this in the literature show a development in common themes that make up social sustainability. Black describes the social perspective of sustainability as relating to the social values, identities, relationships and institutions that are able to effectively be maintained into the future [42]. He suggests themes such as reciprocity and equity, the maintenance of individual identity and cultural diversity, and the ability for social institutions to fulfill a community's needs, and to adapt to environmental and economic changes that encompass social sustainability [42]. Murphy outlines that equity, awareness of sustainability, participation, and social cohesion are key concepts within which social sustainability policy can be categorized [48]. Torjman identifies poverty reduction, social investment, and caring for communities as priority areas in social sustainability [49]. From a sociological perspective, Griessler and Littig suggest three core indicators to assess social sustainability, which are, the satisfaction of basic needs and the quality of life, social justice, and social coherence [50]. In the business context, social sustainability tends to be used interchangeably with terms such as Corporate Social Responsibility, and is commonly researched as a part of environmental or economic sustainability rather than a standalone dimension of sustainability [51].

3.3. A Fourth Pillar—Cultural Sustainability

The cultural perspective is a relatively new direction in sustainability thinking, with growing interest in policymaking and among scholars to consider cultural sustainability as a fourth pillar [52,53]. In many past discourses of sustainability, the cultural perspective has not been recognised as a dimension on its own, rather has been associated alongside the social dimension because of shared themes [48]. Hawkes distinguishes between cultural diversity and social equity and argues that they should be treated as two distinctive pillars of sustainability [52]. Soini & Birkeland also suggest that cultural sustainability is linked but not equal to issues of social sustainability, regardless of whether cultural sustainability is a separate pillar or not, by adopting the view that culture divides humans from nature, and humans from other humans [53].

Similar to the social perspective, cultural sustainability is both broad in what it encompasses and poorly understood, depending on what culture refers to and its relationship with the environmental, economic, and social pillars of sustainability. In many contexts, culture is understood as cultural capital, usually in the form of cultural heritage, tangible and intangible. In this sense, cultural sustainability is associated with maintaining cultural vitality and preserving cultural identities for future generations through the protection of cultural heritage [54,55]. Culture can also be seen as a resource for economic vitality as well as for local and regional development in the face of globalization [56]. Some other scholars emphasis the diversity and locality of different cultures, acknowledging the diversity of perceptions, values, and lifestyles linked to certain contexts need to be considered to achieve sustainable development [57,58]. Finally, cultural sustainability can also refer to a cultural shift that promotes the transition to sustainable practice by calling for societal change in values, consciousness, and attitudes, and the balanced relationship between humans and nature [59].

4. CEA and Sustainability

The modern-day concept of CEA is deeply related to its potential for providing fresh produce to urban populations in a more sustainable manner than conventional farming. Here, we review how CEA has been positioned and discussed as sustainable in various dimensions across the literature, from a holistic approach of sustainability.

4.1. Environmental Sustainability of CEA

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. [14]. 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 [60]. 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 [61]. 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 [14,23,62].

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 [14,23,62]. 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 [60].

Despite all these potential benefits, CEA may still cause negative impact on the environment. Another major feature of CEA is that these systems usually operate 24 h per day with temperature fulled controlled, and using artificial lights instead of natural sunlight. Considerably higher amount of electricity will be needed to articificially maintain the optimal growing conditions for crops across different seasons all year round, and thus contributes to significant energy use and GHG emission [3,61,63]. Advancement in renewable energy technology and its implementation is crucial to address this concern to strengthen the sustainable image of CEA [64]. In addition, CEA operates in concealed buildings, and the construction of these buildings represents a considerable source of carbon emission [65]. To reduce environmental impact of CEA from this perspective, some vertical farms were built using abandoned or re-purposed buildings to avoid cabon emission resulting from newly constructed buildings [14,66]. A recent case study acccssing 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 [67].

4.2. 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 relating to enhanced productivity and efficiency. Operating indoor on a 24 h 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 [14]. 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 [14,23,62].

While many of these economic advantages seem to be promising for CEA systems, there are many challenges acknowledged as well. Start-up cost and capital investment 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 [14,23,62]. Being located in or close to urban areas also means expensive land and infrastructure cost [14]. 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 [60,62]. 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 [68].

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 [60].

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 [69]. 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.

4.3. 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 [39]. 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 [21]. 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 [70]. 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 [71]. 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 [60,62].

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 [14,23,72]. The disruption of CEA to traditional farming was also considered in the transitioning process to CEA operation [14]. 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 [72]. 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 [73]. 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 [74]. 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 [14].

5. Consumer Perceptions of CEA and Sustainability

In this section we review existing literature concerning consumer perceptions and attitudes towards CEA, especially how sustainability features of CEA are perceived by consumers, and how these perceptions relating to sustainability may affect consumer acceptance of CEA productions. The purpose is to idnentify whether multiple dimensions of sustainability was communicated to consumers, whether perceived sustainability of CEA was measured from multiple dimenisons, and whether perceived sustainability was found to have positive impact on consumer attitudes and acceptance of CEA.

5.1. Framing of CEA in Consumer Studies

Because of its fast development with various characteristics and different forms, CEA has been referred to by different terminologies in consumer studies, including vertical farming, indoor farming, and plant factory, with or without a comprehensive description of CEA and its associated features. One of the earliest consumer surveys on CEA conducted in Japan, introduced respondents to the concept of 'plant factories' simply as where growing conditions were controlled and optimised, chemicals rarely used, and high quality vegetables produced year-round in mass volume, in addition to the potential of creating regional job opportunities [75]. Additionally, conducted in a Japanese context was another study which framed CEA production as "vegetables grown using artificial light" and "vegetables grown hydroponically" [76]. Another study conducted in the United States of America (USA) used an experimental auction and survey to compare respondents' preference for lettuce produced in 'vertical farms', 'greenhouses', and 'field farms', respectively. Participants were given information on the source and usage of light, land, water and electricity, plus additional information about yield and pest control methods used across these three farming systems [77].

Some recent studies reported more detailed descriptions of how CEA systems and its production were presented to their respondents or participants. For example, Jürkenbeck, Heumann, and Spiller provided the original texts used to describe different versions of 'vertical farms' to respondents [27]. They framed the large scale of indoor vertical farming using key words including "grown in empty warehouses, 70% less water usage, optimally supported by individual LED lighting, short transport distances and environmentally friendly, energy usage, soilless and nutrient solution, no pesticides, and all year round production" (p. 18). The work by Ares, Ha, and Jaeger also provided the full text, describing different characteristics of vertical farming including key words "closed buildings, vertically stacked, controlled growing conditions, nutrient-rich water, soilless, greater variety, high energy requirements, premium prices, automated, robots, daily supply of fresh produce, near city, reduce carbon emission, securing food supply, yield up to five times more, land be returned to nature" [78] (p. 3). In this study, the full descriptive text also included two paragraphs that briefly highlighted the need to "feed the world" and "the transition towards plant-based foods" to "protect our environment".

Our review found no consistent definition or description of CEA to respondents across these consumer studies. Most of the work captured the key features of CEA and vertical farming including stacked layers, LED lighting to replace sunlight, nutrient solutions to replace soil, and high yield. In addition to these technical features, studies have adopted different framing of CEA in their research designs with additional information to address the potential effects of CEA for specific research interests and purposes. Additional information mainly states benefits of CEA, and in some studies the background information to set the scene of "why CEA is needed". Some studies presented negative information or disadvantages of CEA to respondents (using different wording), while others did not. In addition to inconsistency of the information given to consumers in these studies, scholars also noted recently that, although CEA businesses had been increasingly established worldwide, research continues to find significant gaps in public awareness and understanding of CEA across the world [29,77,79–81]. Thus, what information of CEA was provided to consumers, and how it was presented in the research, might have a strong influence on consumers' perceptions of CEA, and subsequently affect the research results pertaining to consumers' perceptions and acceptance of CEA and its production.

5.2. Consumer Perceived Sustainability of CEA—Environmental-Centric

Early studies on consumers and CEA, as well as some more recent work, highlighted a strong research interest in understanding consumers' knowledge and familiarity of CEA, their perception of CEA production with respect to safety, nutrition, naturalness, and their willingness to pay. These studies either did not include sustainability related measurements in their research design, or, if included, did not further investigate how sustainability may affect consumer attitudes and acceptance of CEA.

Amongst existent studies, the work by Jürkenbeck et al. to compare consumer attitudes towards three different vertical farming systems, was one of the few studies that had a more specific interest in consumers' perceived sustainability of CEA [27]. Both consumers' attitude toward sustainability in general, and consumers' perceived sustainability of three vertical farm systems, i.e., vertical home farm, in-store vertical farm, and indoor vertical farm, were investigated in this study. Here, "attitude toward sustainability" was measured by how respondents perceived the importance of a "healthy diet", "environmental friendliness", and "combating hunger", with no explanation on why these three elements represent one's overall attitude toward sustainability. Similarly, "perceived sustainability" of different vertical farm systems was measured by the extent that respondents agreed with statements about the system being "useful/useless", "environmentally friendly/environmentally unfriendly", "convincing/questionable", "trendsetting/old-fashioned", and "stands for a sustainable production". The study provided no reference to how "perceived sustainability" can be represented by the above elements. This study concluded that perceived sustainability is the main driver of consumer acceptance of vertical farming, and attitude toward sustainability has a slight influence on perceived sustainability.

The work by Ares et al. also included several sustainability related statements in their measurement of consumer attitudes towards and opinions of vertical farming, including energy consumption, the potential to secure global food supply, the returning of farm land to nature, and the reduction of carbon emissions [82]. The study questioned consumers in China, Singapore, the United Kingdom (UK) and USA, and concluded that the characteristics (i.e., higher yield, reduction of carbon emissions, and securing access to food) of vertical farming that aligned with the UN Sustainable Development Goals were identified as key drivers of positive attitudes. It stated that these statements were developed by the authors and were revised following feedback from colleagues, and "it was consumers' responses to these statements that was of interest, rather than the validity of the statements themselves" (p. 4).

Despite being inconsistent in the measurement of sustainability related constructs with regard to consumers' perceptions of CEA, research showed growing interest in exploring the role of sustainability in affecting consumer attitudes and behaviours concerning CEA. It was generally agreed that sustainability is gaining more weight in driving consumer acceptance of CEA. However, the perceived sustainability of CEA varied depending on factors including context, consumer group, and form and scale of CEA facilities. For example, Jürkenbeck et al. suggested that the larger the vertical farming system, the higher the likelihood that it will be considered as sustainable by consumers [27]. Another recent research by Perambalam et al. on young adults (who were positioned as the "future consumers" in the study) in Denmark revealed that sustainability was one of the principle drivers for consumer acceptance of vertical farms, yet vertical farming was not widely accepted by this group of consumers [79]. Whilst these consumers believed vertical farms had the potential to contribute to local and greener food production, the vertical farming systems were not inherently environmentally friendly due to their perceived artificiality, i.e., using artificial LED lights and nutrient solutions rather than sunlight and natural soil. It is evident that most of these consumer studies have mainly, if not solely, addressed the sustainability feature of CEA from an environmental perspective.

5.3. Perceived Economic Impact of CEA on Consumers

While economic feasibility and profitability is a core concern for CEA investors, price and willingness to pay for CEA production is a crucial indicator of consumer acceptance from an economic perspective [77]. Although environmental benefits and the potential of CEA to increase healthy food supply have received positive consumer responses, there have been continued concerns and suspicions around how CEA production is affordable and accessible to end consumers [80,83]. For example, the study conducted by Coyle and Ellison reported positive consumer attitudes towards CEA lettuce regarding its potential to solve environmental problems, reduce prices, and improve the standard of living for future generations. However, this study also revealed a lower willingness to pay for CEA produce due to lower cost expectation of CEA lettuce as a result of mass production [77]. Ares et al. also reported in their study that the premium price of CEA production contributes to negative perceptions of CEA [82]. Indeed, to increase profitability, current CEA operations tend to target high-end consumers who are willing to pay a premium price for high quality produce, which may compromise the potential of CEA to contribute to the UN Sustainable Development Goals of zero hungry and nutrition equity, especially for less developed regions where consumers are more sensitive to food price [23,60,84].

5.4. Social Impact of CEA and the Absence of Cultural Sustainability

Only a few consumer-centric studies, and a relatively small number of authors, have employed social and cultural lenses to understand consumers' perceptions and attitudes towards CEA.

Specht et al. investigated the social acceptance of various forms of urban agriculture businesses, including vertical farming [28]. The study used the following parameters to evaluate respondents' perceived societal impacts of urban agriculture: contributes to environmental improvements (in terms of climate, resources, transportation); contributes to education; generates opportunities for new leisure activities; contributes to new job creation; contributes to cooperation/community building; improves societal views of "farming"; promotes inappropriate animal keeping, and leads to increased noise, dirt and odours. Their study revealed that urban agriculture systems that are consistent with traditional images of agriculture/horticulture production with fewer high-tech applications were more likely to be accepted, whereas systems that were associated with intensive or high-tech agriculture, such as vertical farming, were less accepted. The results also suggested that urban agriculture forms that were multifunctional by combining commercial goals with ecological and social goals could potentially achieve the highest degree of social acceptance.

Another study by Specht et al. compared vertical farming with five additional new approaches to food production [80]. This study also revealed that with regard to the social dimension of sustainability, improving the supply of fresh and healthy food was perceived by stakeholders as the major benefit of new approaches to food production. This benefit was particularly relevant to vertical farming given its potential high yield. The authors also highlighted that education and re-connection of consumers to their food was a desired social benefit of new food production approaches, however facilities like vertical farms are not likely to allow public access, thus could not be used for promoting this social benefit. Similarly, a study recently conducted in China suggested that vertical farms can offer social benefits by adopting a multifunctional approach [85]. Survey results of this study indicated that, rather than being purely a highly efficient production facility, vertical farms located in cities are expected to offer other functions including education, farming experience (plant and harvest on your own), and other recreational functions such as catering and shopping.

These studies have highlighted the social expectations of CEA, and how failing to meet these expectations may result in social conflicts instead of achieving social sustainability, especially when compared with other urban production approaches such as community gardens and rooftop gardens. Little specific recognition of the cultural dimension of sustainability was found in these studies in relation to consumer attitudes and acceptance of CEA, if not generally included in the discussion of the societal impact of CEA. Similar to the social sustainability dimension, this may be partly attributed to a lack of consensus of what cultural sustainability refers to and how it can be measured. More research needs to consider the cultural implications of CEA in the future in order to identify any cultural concerns of CEA and ways to address these concerns.

6. Conclusions and Future Research

This review evaluated sustainability as a concept encompassing environmental, economic, social and cultural aspects, and further evaluated how CEA has been framed as sustainable in scientific discourse, with a specific interest in consumer perceived sustainability of CEA and how these perceptions may effect consumer acceptance of CEA and its production. Under the overarching theme of UN Sustainable Development Goals on the international agenda, sustainability is commonly agreed to be an inclusive concept that covers environmental, economic and social dimensions. The additional cultural aspect of sustainability has also been gaining more attention recently.

Specifically for agriculture and food production, the narrative concerning sustainability is commonly set around the need to feed a growing global population under resource constraints and the threat of climate change; novel agri-food technologies such as CEA are then positioned as the potential solution to the dilemma of feeding the world whilst preserving the planet. Whist the conflict between the growing demand for food and the finite natural resource for growing food is heightened in this narrative, we found much less attention has been given to the social and cultural sustainability of the current food production system. Across the literature, our review identifies a dominant focus on environmental sustainability addressing CEA's feature of optimal production value and minimal environmental input/impact, usually from an efficiency-enhancing and cost-saving angle. The environmental focus may be partly because of the nature of agriculture and its dependency on finite natural resources. However, this also signals the lack of holistic evalution of CEA with regard to potential social and cultural issues that can result from its implementation. Although some scholars have raised the importance of evaluating sustainability in a more holistic way and some effort has been put into developing suitable methods for evaluation, it is also acknowledged in the literature that measuring the social and cultural effects of a new technology is very challenging.

Our review of existing research on consumer acceptance of CEA also finds no consistency in the description of CEA when it was introduced to participants/respondents in these studies, and sustainability features were not necessarily included in the description. Such inconsistency in the description of CEA may be partly due to the fast development of CEA over time, which has resulted in diverse forms of CEA operations in different regions. Additionally, scholars from different backgrounds and contexts may also adopt different approaches and research designs for their own research interests in different features of CEA. Amongst those studes which did communicate sustainability features of CEA to respondents/participants, authors mainly drew on the potential environmental benefits/impacts as the evidence of CEA being sustainable, leaving the social and cultural impacts on sustainability largely ignored.

With regard to consumers' perception of CEA, perceived safety, taste, nutrition, and naturalness of CEA were more intensively researched along with the willingness to buy CEA produce, especially at a premium. Consumer perceived sustainability of CEA was measured in some studies, yet there is a lack of consensus on the measurements used in different studies. Additionally, findings about how perceived sustainability may affect consumer attitudes and willingness to pay are not consistent in these studies. The inconsistency in measurements and findings may compromise the synegitic power of these studies in relation to providing insights to both the industry and public policy.

In addition, within those studies that did investigate perceived sustainability of CEA, in most cases only the ecological/environmental aspects of sustainability were addressed. Only a few studies that investigated the social acceptance of CEA extended their inquiry to the social impacts of CEA. In these studies social impacts were framed as a separate category to environmental impact, instead of under a holistic framework to incorporate multiple aspects of sustainability. Cultural sustainability was barely discussed as a potential factor that might influence consumer acceptance of CEA in the existent literature.

Again, this may be partly because of the ambiguity in the conceptualisation and the difficulties in measuring social and cultural sustainability. This also reflects that in the current dissemination and communication of CEA and other new agri-food technologies, the meaning of sustainability might have been narrowed to only encompass environmental impact or being environmentally friendly. Even though in some cases social and cultural impacts of CEA were discussed, such discussions were usually not under the general umbrella of sustainability per se.

Although a number of studies have demonstrated the positive correlation between perceived sustainability and acceptance of CEA, such correlations may have been biased by the framing of information that participants received in these studies. In such studies, it is important to check whether consumers have been given comprehensive information to inform their opinions and decision-making, given that CEA is still not commonly known by the majority of consumers. Furthermore, considerations beyond environmental sustainability are also necessary to encourage stakeholders to readily accept the transition to CEA.

Overall, the literature shows there is a lack of effort in investigating CEA from a more holistic sustainability approach. Our review exemplifies how sustainability becomes environmental-dominant in the context of new agri-food technology, despite that sustainability is commonly agreed to be muti-dimenstional in theory. We call for more work on strengthening the theoretical foundation of sustainability as an inclusive concept as well as more effort on bridging the gap between the inclusive sustainability concept and the uni-dimensional application in research.

For implications to sustainable pratics, this review reminds us the importance of going back to the integrity of sustainability when evaluating new agri-food technologies in order to get a balanced view of its impact on people, products, and planet. Ignoring social and cultural dimensions may result in the failure of obtaining social license to operate.

There are some limitations of the current review. Firstly, only CEA was reviewed as an exampler and more other new technologies need to be reviewed as well. Secondly, this review also did not specifically examine the methods employed in studies of consumer perceptions. Given the ambiguity of social and cultural sustainability in the literature, more exploratory methods will be needed to better conceptulise these dimensions of sustainability. Based on findings of these exploratory studies, we suggest that developing a holistic scale to measure consumer perceived sustainability of agri-food technologies will be very valuable to future work.

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