DECONSTRUCTING THE DISCOURSE(S) OF CONTROLLED ENVIRONMENT AGRICULTURE(S)

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Executive Summary

Recent challenges to food security mean that socio-technical innovations are becoming increasingly visible as alternative ways to produce food – politically, socially, and economically. Controlled Environment Agriculture (CEA) is generating a plurality of opinions and factors which contribute to an extensive discourse around this technology and its social, environmental and economic impact. However, it remains a complex, multifaceted topic with numerous intersecting and overlapping benefits and challenges. This report unpacks the discourse surrounding CEA by listening to and reporting on the diverse views, whilst critically analysing the claims. The report combines a comprehensive discourse analysis with in-depth interviews with twelve experts in the field. Through this amalgamation of sources rooted in both the theory and practice, we conclude that there is as yet no single straightforward discursive narrative on the benefits and impacts of CEA for future food production.

The report begins by discussing the lack of consistent definition of CEA, ranging across a full spectrum of control levels. This lack of agreed definition is significant as it is challenging for a coherent narrative to emerge, or for policies and regulations to advance.

An important theme in the discourse is around the Environmental Impact of CEA. There are numerous interconnected factors that contribute to the environmental impact of this technology. In this report, we display the spectrum of perspectives on the topic and consider the trade-offs of this technology compared to traditional food production. Positive factors, such as reductions in food miles, food waste, use of pesticides and fertiliser, and efficient water usage are contrasted with negative environmental impacts of construction and energy use. We use both empirical and discursive evidence to discuss these factors to provide a balanced discussion which confronts this complex topic.

CEA is often advocated as a potential solution to Food Security. This report discusses the plethora of factors that relate to food security including the cost to consumer, crop range, location of the food and the nutritional value of the produce. We conclude that all four of these factors need to be considered if CEA is going to have significant impact on food security. In this report, we further discuss the need for community engagement and education around CEA produce. This could be beneficial for improving the public perception of the food grown, which could be key to the technology's success and wider societal benefits.

External Factors that contribute to CEA are also discussed, including, Covid-19, Brexit, climate change and geo-political factors. Each of these highlight vulnerabilities in current food systems and we discuss the challenges and opportunities for CEA in this context. The Global Opportunities for CEA are then considered, discussing potential implementation in the Middle East as well as Developing Countries. There are many benefits to CEA in these contexts, however, the report also discusses the many barriers that would need addressed for this to come to fruition.

Finally, the report concludes by considering the Future of CEA from the perception of the interview participants. We found that there is considerable support for CEA from some stakeholders with conditional support from other quarters. There are several potential future scenarios that CEA may take, and this report highlights many of the critical considerations that need addressing while the technology is in its infancy for CEA to be considered a realistic technology for future food security and to tackle current socio-economic issues outlined in the report. Due to the emergent nature of CEA, much of the evidence regarding the technology's potential is not yet proven, consequently, this report aims to highlight the areas that require further research as the technology develops.

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1. Introduction

Rapid global population growth, accelerated urbanisation, global health and nutrition, and geo-political crises have led to increasing concerns that existing food systems are unsustainable and unable to deliver food security in the future, especially in cities (Thornton, 2020; Lawrence, Lyons, & Wallington, 2010). Environmental threats, such as climate change, soil degradation and decreasing water resources, have exacerbated such concerns (Specht et al., 2014). Technological solutions, which offer the potential to increase the productivity of food systems in an environmentally sustainable manner, are increasingly entering public and political discourses. Controlled Environment Agriculture (CEA) is one such technology that has potential to contribute to food security.

CEA is not a new concept, but has piqued academic interest in recent years, partly due to Dickson Despommier's concept of 'vertical farming' (Goodman & Minner, 2019; Benke & Tomkins, 2017). Despommier's vision of vertical farms are ambitious 30-storey skyscrapers where crops are grown in vertical stacks, resulting in high yields of certain crops using just a fraction of the land that conventional agriculture would use for a similar yield (Despommier, 2009). Many remain sceptical of the practicalities of Despommier's visions' central arguments, but his ideas have led to increasing interest in the role of vertical farming and CEA (in urban areas) as ways to tackle food insecurity. Though the science behind CEA continues to be developed, there is a lack of research surrounding the social, economic, and political consequences of this technology (Gómez et al., 2019; Goodman & Minner, 2019). Questions therefore remain about the impact of CEA on existing food and social systems.

This report examines claims made about the environmental, economic, and social benefits and challenges of CEA. This is conducted through interviews with a panel of 12 stakeholder experts and comprehensive discourse analysis of academic and popular literature. Stakeholders included plant scientists, entrepreneurs, investors, representatives from farmer advocacy groups, and non-governmental policy representatives. This report aims to unpack the complexities of CEA by challenging the claims made about impact through an interdisciplinary approach to socio-technical innovations.

1.1 What is CEA?

The term Controlled Environment Agriculture (CEA) refers to a range of technologies related to food production. Niu & Masabni (2018) define CEA as:

"Any agricultural technology that enables growers to manipulate the growing environment for improved yield and quality. CEA production systems include high tunnels, greenhouses, and indoor vertical farming, as well as hydroponics and aquaponics."

Benke and Tomkins (2017) define vertical farming as:

"Farming which involves much greater use of technology and automation for land-use optimization" and go on to state that "A modern greenhouse operates as a system, therefore, it is also referred to as controlled environment agriculture (CEA)".

Among our stakeholder interviewees, there was some variation in opinion about the essential elements that define CEA; their definitions emphasised the importance of controlled elements, particularly regarding light, temperature, and microclimate. The use of technology was a reoccurring theme among participants' definitions, many of which mention use of LED lights; heating, ventilation, and air conditioning (HVAC) systems; and water recycling. Other factors included being pesticide free and controlling the fertiliser and nutrients. Attention was drawn to the fact that CEA is not limited to plant growth, but could include insects, poultry, and aquaculture, as each of these require a 'controlled environment'.

The range of perspectives is illustrated in Figure 1. This potential range of definitions is significant because it is challenging to develop policies and regulations for socio-technical innovations without clear agreement of what is being governed. In this report we focus on the more controlled end of the spectrum such as vertical farming often referred to as Total CEA or TCEA. TCEA technologies and innovations are much less developed than polytunnels and greenhouses, hence the socio-economic debates are more contested than with other forms of CEA.

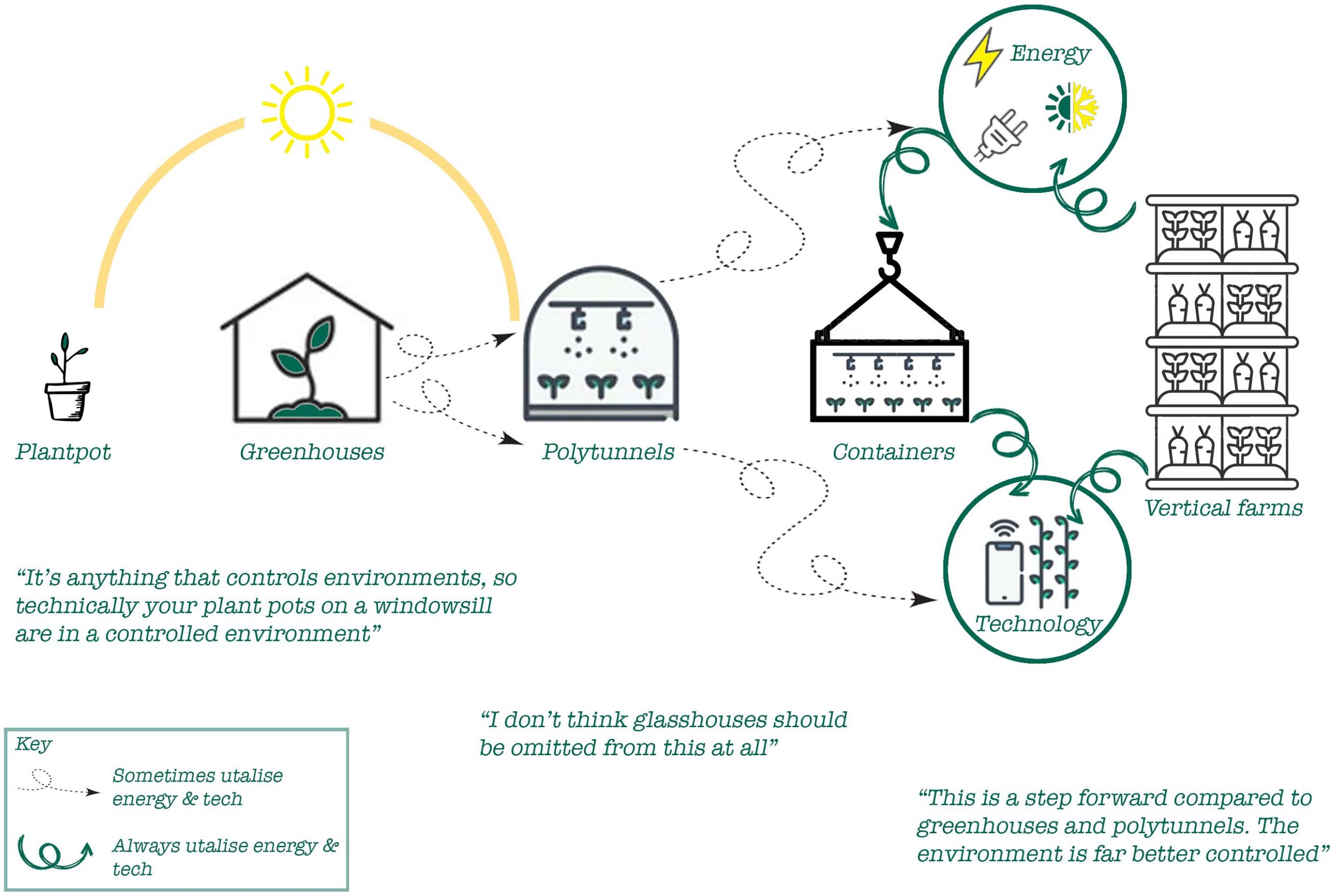


Figure 1: What is CEA? Spectrum of control

2. Climate Change and Environmental Impact

In the literature, CEA is regularly cited as a resilient means of growing produce in response to climate change impacts including extreme temperatures, floods, droughts and the increasing pressure from pests and disease (WayBeyond and Agritecture, 2021). During the interviews, a consistent theme was that CEA creates 'optimal' farming conditions where elements such as heat, light, and water can be manipulated. Participants stated that CEA protects from external events such as floods, droughts and heatwaves.

CEA crops are also protected from animal waste and pests. One of the scientists we spoke to stated:

"I am controlling the lights for the plants. This is the most important in my opinion. We control the temperature. We control the humidity. We control the watering, how much water and how frequently we add to the plants. And we control the level of the carbon dioxide. And of course, we control what is the composition of the watering solution, what we use for feeding the plants." (Scientist)

This level of control and predictability was considered a benefit of the technology by many of our interviewees. They felt that it allows the grower to advance certain controlled characteristics that they want to pursue:

"That's one of the potential advantages of CEA that if you have a relationship with a plant scientist you can take things a step further and do things like change your light levels, you can change nutrient inputs, your temperature and so on to grow the plant in slightly different ways and really pursue certain taste characteristics." (Entrepreneur)

Discussion of optimal farming conditions led many participants to discuss the perceived environmental benefits of CEA. This has been illustrated in the spectrum diagram in Figure 2 showing the plethora of factors that contribute to the overall environmental impact of food production. This is a complex discussion with positive and negative views depending on the stakeholder. Figure 2 displays a quote that highlights the construction of the 'farm' also has a carbon footprint, which should be considered when debating the environmental impact of CEA. However, we note that not all CEA facilities are built in new buildings, with one of our participants growing in a basement of an existing building, which reduces the environmental impact and capital cost of their farm. Notably, one interviewee who works both in traditional agriculture and CEA discussed the ways in which field agriculture is evolving and innovating to reduce its carbon footprint. They went on to state that their outdoor farming business will be NetZero by 2035, showing that field agriculture is also changing its environmental impact over time to enable it to compete (in environmental terms) with developments such as CEA.

The same participant criticised the environmental claims of CEA on the basis that most CEA farms input additional energy for lighting and environmental control, while traditional farms rely on the sun and wind. A second participant considered this criticism and discussed that the environmental impacts of additional energy usage can be tackled through using renewable energy. Several articles have suggested the possibility of incorporating renewable energy sources into CEA farms depending on the natural resources available to them, which could cut fossil fuel use and reduce energy costs (Al-Kodmany, 2018; Benke & Tomkins, 2017; Despommier, 2009). . Relatively little is known about how much these systems would cost to install, or how much income they can generate. In a report about the vertical farm Gotham Greens in New York, Puri (2011) claimed that the energy needs of the farm are met "in part" by solar panels, but does not provide details of the costs surrounding this. To investigate the economic feasibility of incorporating renewable energy sources into CEA farms, Zeidler et al. (2017) simulated solar panels in two locations, Munich and Aswan, to calculate how much income they could generate through current tariff rates. They found that even in sunny locations, solar panels would be unable to meet the energy demands of CEA farms, and that the high cost of solar panel installation would outweigh the marginal income that could be generated. However, the entrepreneurs we spoke to were very positive regarding renewable energy generation, discussing Scotland's potential for further wind power to reduce the environmental impact of a CEA farm. Currently, the capital costs of installing renewable energy

on a CEA farm remain variable, and more cost-benefit studies are required.

One of the positive environmental impacts of CEA relates to the reduction of water, pesticide and fertiliser use. There is empirical evidence that pesticide use through conventional farming has negatively impacted the health of all the ecosystems in the world (Gould, 2015). As such, an environmental benefit of CEA is that it uses reduced pesticides compared to traditional farming, albeit with a reduced range of crops. This was explained by one of our interviewees who said:

"If you are in a nitrate vulnerable zone…then you've got to be a bit careful with run-off. However, in these systems again all of your fertiliser is fertigation, so it's in the water and it's recycled around the system again, so you've got no run-off concerns. You're also using less fertiliser because again you're only applying fertiliser to the plant and you're not applying it to the ground." (Farmer & Entrepreneur)

Many advanced CEA facilities are reducing their water usage to decrease environmental impact. Supporters of CEA assert that it uses less water than irrigated conventional agriculture, something which could be particularly valuable in the future as global water resources become increasingly scarce and subject to competition (Cho, 2011). The exact amount of water used depends on the technology that is employed and the crops being grown, but using hydroponics and recycling rainwater and wastewater, via a the common place closed loop system, can cut water usage considerably (Specht et al., 2014).

One of the interviewees we spoke to discussed that their facility's water is harvested rainwater that is efficiently circled through the system and picked up by the plants:

"We're harvesting our rainwater for our crops, so everything that comes off the roof will supply what we need. It goes around a system with a couple of filters, some UV filters and paper filters, and everything that comes back from the plants goes through that system again as well, so water usage is again much better than traditional ag." (Entrepreneur)

However, one participant revealed that using recycled water can cause crop disease:

"And the nice thing about these controlled environment things is they are set up to sterilise the water, but they are still recycling a lot of their water to control their inputs and I guess to help them be more sustainable, but at the same time it is a risk that these root pathogens or waterborne things will find a way round some of their sterilising regimes eventually." (Plant Scientist)

Overall, water usage does appear to be lower in CEA farms compared to conventional farms, especially if hydroponic systems are used, as this allows water to be recycled. In a study on lettuce, Barbosa et al. (2015) found that conventionally grown lettuce had a water demand of 250 ± 25 L/kg/y, while hydroponically grown lettuce had a far lower demand of only 20 ± 3.8 L/kg/y. One vertical farm in New York also reported that their production system used only 5% of the water used in traditional agriculture (Cho, 2011). Rainwater and wastewater may be potential sources of water for

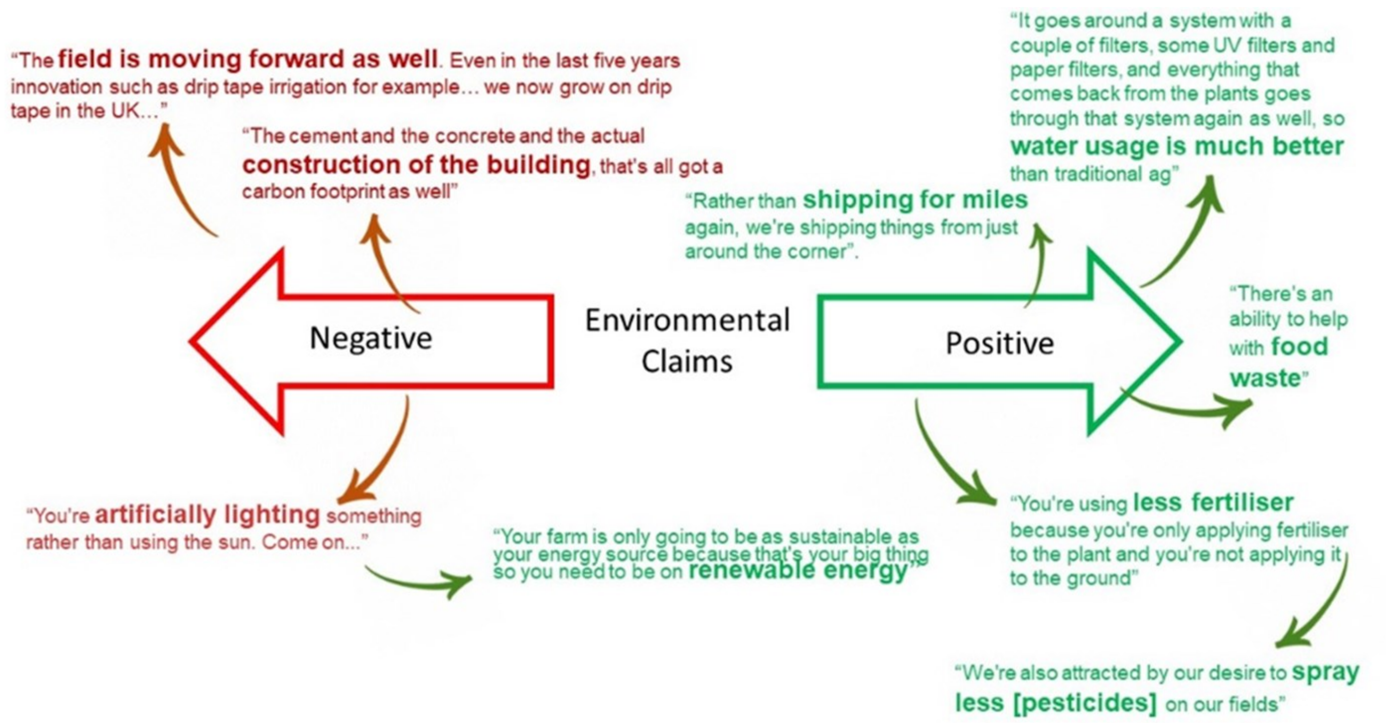


Figure 2: Polarised views of CEA's Environmental Claims

CEA farms, but the ability to take advantage of these water sources varies between production systems (Goldstein, Hauschild, Fernández, & Birkved, 2016). Therefore, as Gomez et al. (2019) argued, the net effect of water consumption in CEA systems is yet to be determined, as it is influenced by location, infrastructure, and technology.

A final claim for the environmental benefits of CEA is regarding the reduction in food miles and food waste (also discussed in Section 3). The distance travelled by crops from the place of production to the place of consumption is one of the main sources of fossil fuel emissions within agriculture. Despommier (2009) claims that these "food miles" could be reduced considerably when growing produce through CEA, since crops could be grown closer to the place of consumption. This may be particularly relevant for cities, who import most of their produce. Growing crops in urban vertical farms could reduce food transportation and associated fossil fuel emissions considerably. Additional claims include that because food has less distance to travel, the produce could be fresher and less likely to spoil, thus reducing food waste (Benke & Tomkins, 2017). This appears to be one of the primary drivers for CEA discussed by our interviewees:

"One of our big bug bears is things being shipped all the way around the world." (Entrepreneur)

The potential reduction in food miles could mean crops have a longer shelf life as they spend less time in transit. This is a positive for reducing food waste, as the crops spend maximum time available to consumers, thus are unlikely to be wasted through short sell by dates. To balance this discussion, through our literature analysis we note that Specht et al. (2014) highlighted that many advocates of CEA have fallen into what he calls **'the local trap'** where they assume that local food is inherently more sustainable than food that has travelled further. We must be cautious in treating local food as inherently more sustainable, especially since the benefits of fewer food miles varies with location (Section 3.1 discusses challenges of siting CEA in urban areas). Additionally, considering only food miles as an indicator for sustainability can be limiting and other factors influencing growing conditions need to be taken into consideration (Scharber and Dancs, 2016; Blanke et.al., 2005; Edwards-Jones et. al., 2008).

The environmental impact and ability to alleviate climate change concerns of CEA is thus a complex discussion as it relates to a plethora of factors. Figure 2 highlights the positives (such as reduced water, pesticides, fertiliser, food miles and waste) and the negatives (energy use and building construction). Sceptics of CEA have criticised the high energy inputs required, arguing that this negates its other environmental benefits (Goldstein et al., 2016). The amount of energy used depends on the technologies being used; LEDs may be used for lighting while HVAC systems may be used to control temperature, humidity and air purity (Januszkiewicz & Jarmusz, 2017). Advocates of CEA have argued that energy costs could be reduced in the future, through a combination of technological advancements, and integration of farms with existing buildings. In CEA farms that make use of artificial lighting, this is the most energy intensive input (Zeidler et al., 2017). Some have suggested that future developments in LED technology could cut this energy usage (Asseng et al., 2020), but there is still much uncertainty about the amount of reduction and given recent price rises any reduction may be offset by real world energy cost increases.

Alternatively, CEA farms can arguably take the form of greenhouses, which would combine natural sunlight with artificial lighting and reduce energy use (Asseng et al., 2020). Within cities, greenhouses are not always an option, as it can be difficult to get sunlight at ground level in dense urban areas (Ackerman, Dahlgren, & Xu, 2013). In terms of heating and cooling CEA farms, some have argued that integrating farms with existing buildings could be more energy efficient. In cooler climates, farms built on rooftops may be able to take advantage of the waste heat from the building below, cutting heating costs (Ackerman et al., 2013). In warmer climates, there is some evidence to suggest that the cooling system of a rooftop greenhouse is more energy efficient than air conditioning in terms of cooling the building below (Caplow & Nelkin, 2007).

CEA-produced food appeared on the agenda (and menu) of the environmental COP26 conference in Glasgow in November 2021. Advocates of the technology were advertising its environmental impact, and it gained press that the World Leaders may dine out on 'vertically farmed' vegetables (Watson, 2021). During COP26, one of the large CEA organisations gained £42 million of funding with the rationale that it is an environmentally friendly form of agriculture (IGS, 2021). Through our research, we conclude that there are potential environmental benefits to CEA, however these can vary depending on the technology used so it should not be assumed that CEA will always reduce the environmental impact of food production. Environmental challenges remain for CEA.

3. Combating Food Insecurity?

The main arguments in support of CEA in terms of social benefits are oriented around the concept of food security. In the context of rising global populations and accelerated urbanisation, there is an increasing need for healthy food that is affordable and accessible to all. Food security is about more than just the quantity of produce available, but also about its nutritional value and accessibility, including price. By accessibility, we are referring both to the proximity and the cost of food for people.

Food security is a particular issue in areas where there is a lack of shops selling healthy and affordable food, also sometimes referred to as "food deserts". Food deserts can occur in both rural and urban areas and they disproportionately affect those living on low-incomes (Ackerman et al., 2012). Many CEA farms claim to be able to address this problem by selling fresh produce directly to local shops (Al-Kodmany, 2018). However, there are CEA advocates that are admittedly cautious in their claims of food security. They do not claim that CEA is a silver bullet which can single-handedly deliver global food security, but instead that it may be able to contribute to a food system which can provide access to nutritious and sustainable food on a more local scale (Kagan & Riemenschneider, 2018), thereby increasing regional and national food security by providing more home-grown fresh fruit and vegetables and reducing reliance on imports.

There are several reasons why our interview participants felt reducing food miles is potentially advantageous for the UK food system including they feel that it makes the food system more resilient to external political or environmental factors; it is thought to be more environmentally friendly, which is increasingly important to help tackle the climate crisis, and that it gives food a longer shelf life with possibly better nutrition. These points were expressed by interview participants who noted:

"I think probably one of the advantages of producing food in-country rather than in import is that the shorter supply chains tend to be more resilient to shock so they can more quickly come back on stream in many occasions." (Plant Scientist)

3.1 Siting CEA in the food chain (physical):

To make the most of these benefits, participants went on to consider the ideal location for CEA farms to be sited. The potential location of farms is a thought-provoking and complex topic as there are a range of benefits and challenges to the various locations. Many supporters of CEA express that this form of agriculture is well suited to urban sites as it brings food closer to the consumer, and that there are many brownfield sites or derelict buildings which they can use to reduce costs. However, through our literature review, we discovered that many cities have strict zoning laws which determine how land is used, and agriculture is often not one of the land uses included in the zoning code. In these cases, planners will need to work out how agriculture in cities can be integrated with other land uses (Goodman & Minner, 2019). There are some promising examples of cities that have already adapted their zoning laws to become more receptive to urban farming. New York has adapted regulations to encourage educational and commercial farms, as well as exempting rooftop greenhouses from height and floor area limitations. Chicago has also included commercial rooftop farming into its zoning laws (Thomaier, 2017). Mok et al., (2014) highlighted that urban farming is yet another land use which could be trying to compete for space, energy, and water within cities, therefore, effective planning will be vital to resolve tensions between different land uses and different resource demands.

There may also be restrictions on which buildings can realistically be converted for CEA farms. Large rooftop greenhouses can only be constructed on buildings with high load-bearing capacities (Specht et al., 2014), and must also have appropriate water and energy infrastructure (Thomaier, 2017). Vertical farms will also have to comply with planning laws designed to minimise disturbances to the neighbourhood (Thomaier, 2017). Thomaier (2017) found that although landowners were receptive to vertical farming, they were discouraged by its financial and logistical barriers. Through discussion with our interviewees, it is evident that many new CEA farms are in urban areas, and that these are often successful. However, when sourcing potential stakeholders to interview, we noted that there were many urban CEA farms who were not yet sustainable businesses, thus, it is not a guaranteed success. Nevertheless, many participants that we interviewed considered that converting an existing building can work well to create a farm in urban centres which require fresh food:

"In cities inherently you've got a lack of space, but especially in Glasgow you've got quite a lot of old derelict buildings just sitting there doing nothing and you can convert them to productive spaces where food can get grown…at the end of it you get these farms which are maybe in the heart of a food desert they call them, especially these community farms." (Entrepreneur)

3.2 Siting CEA in the food chain (Community engagement):

Following on from this, participants noted several social benefits of bringing agriculture closer to consumers. This included community engagement, education, and healthier eating:

"There's no reason why it couldn't have even community space in it or educational space or the school could take a little corner of it or whatever, you know, that you could somehow make them feel a bit like this is a place producing our food." (Food Policy NGO)

Some participants gave examples of CEA farms that collaborate with schools, universities, and local communities:

"Farm Urban as well do have a vertical farm, but they also do a lot of the educational side of vertical farming, so they do workshops in schools where kids go build this little hydroponic box, how does it work, what's the benefits of it, climate change, all that sort of stuff." (Entrepreneur)

This positive behavioural change is a significant potential benefit to CEA. CEA farms can become places where children can learn about food and nutrition as well as environmentalism and sustainability (Specht et al., 2014). When engaging and educating consumers, CEA must equally ensure that it is not 'greenwashing' consumers by creating an impression that the product is more sustainable than it actually is. To do so, proper data should be collected to not rely on general averages or anecdotes. There is a danger that greenwashing can slow progress toward true sustainability thus CEA farms must ensure robust data collection to support their claims and improvements to environmental sustainability (WayBeyond and Agritecture, 2021).

Food deserts disproportionately affect those living in low-income neighbourhoods, and some see potential for CEA farms close to these communities. A challenge with this remains the range and price-point of CEA produce. While food deserts are partially due to lack of availability of fresh produce, cost may also be a factor deterring some consumers. One interviewee confirmed this by stating:

"We're not going to solve insecurity by growing high value posh micro herbs." (Farmer & Entrepreneur)

Coyle and Ellison (2017) researched consumers' willingness to pay (WTP) for CEA produce, looking specifically at lettuce as an example. They found that on average, participants WTP was $2.23 for CEA lettuce, $2.28 for greenhouse lettuce, and $2.36 for field-grown lettuce. This shows that these participants were *not* willing to pay more for CEA lettuce, in fact, were willing to pay less.

CEA producers must consider the price of produce, and that bringing

fruit, vegetables, and herbs closer to food deserts will not be enough to eliminate them. There also remain questions for shops and sellers in food deserts, as the study suggests that customers will not be willing to pay more for these products. This brings to question why shops in food deserts would seek to sell CEA produce in their store as there may well not be a lucrative market. Consequently, consumer preferences may result in CEA produce being sold as a niche item to consumers that are environmentally conscious and those seeking food with reduced pesticide use who perceive it is cleaner.

Siting of a CEA facility is, thus, a significant consideration for those joining the business. Although much of the literature focuses on the importance of bringing fresh produce to cities where large populations live, our interviewees also discussed the importance of siting facilities at the end of supply chains, such as island communities:

"Somewhere like Orkney where it's really salty air and really windy, they struggle to do that [eat fresh] and everything that arrives in the supermarket is like a day to its sell by date so you're not getting things, food, the freshest with its best healthfulness." (Plant Scientist)

Siting a facility in a rural or island community brings produce to an area which typically relies on long supply chains, and so this would allow them to have fresher food and may also have positive social implications associated with local farms and local produce.

Our discussions highlight many of the considerations required for siting CEA farms. If these farms are to bring people closer to their food, then locating them at the end of the supply chain, be that urban or island communities, is desirable. Many of the obstacles with regards to planning and support relate to urban areas, while less is known about policy barriers for CEA in rural contexts.

Through these discussions and literature analysis, it is evident that food security is about more than the quantity of food available, but also about the accessibility of produce (both in terms of proximity, and cost) and about the nutritional value of the food available. The cost and type of crop is fundamental in the success of CEA in urban areas. From our literature review, we found that CEA could make existing food systems more transparent, sustainable, and resilient (Thomaier et al, 2015). In cities in particular, people are increasingly divided from the food production process, which is both globalised and industrialised. By introducing agriculture into urban areas, CEA could make these food systems more small-scale and localised, closing the gap between producer and consumer and increasing resilience. While it is said that CEA can bring food closer to the consumer, more evidence is required to support the financial practicalities of this. Figure 3 is a sketch diagram showing some of the considerations of CEA for food security. Overall, the discussion shows that there is a need for healthier, more nutritious produce in the Scottish food supply chain. As such, the following section will consider CEAs role in this.

3.3 Health, nutrition, and crop range

There are concerns that food security for urban residents is unlikely to be achieved through CEA because the wrong kind of crops are being grown. Leafy greens and herbs are the most grown CEA crops because they can sell for higher prices, but some have highlighted the limited nutritional value of these crops (Goodman & Minner, 2019). In addition, CEA produce is typically more expensive than conventionally-grown produce, meaning it is accessible only to the wealthiest consumers rather than communities who face the most problems with food insecurity (Goodman & Minner, 2019). Many

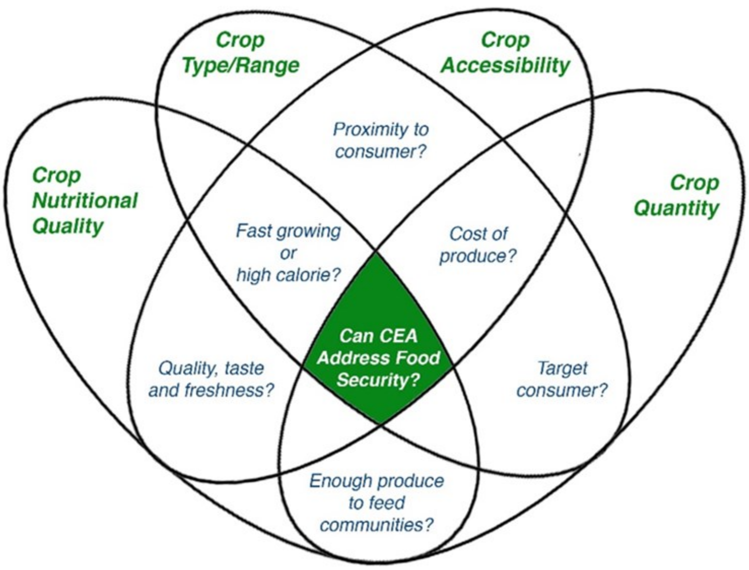


Figure 3: Can CEA address food security?

commercial CEA farms have partnered with large supermarket chains (Walter, Wilson, & Saavedra, 2020), but this does not always improve availability of fresh produce for those in low-income neighbourhoods who already struggle to access supermarkets or lack cars.

We discussed the crop range and nutritional benefits of CEA produce with many of our interviewees. This produced polarised views regarding crop production. One participant, who works in a large farm chain, expressed disbelief in the narrative that CEA can produce vast quantities of produce:

"It's ridiculous really, but a lot of the claims that are being made by vertical farming businesses in terms of the yields that they can achieve and the costs that they can achieve, it's just impossible. You've got people out there saying oh, we can grow a head of gem in six days in a vertical system. You can't. It's biologically impossible." (Farmer & Entrepreneur)

This participant felt that the industry claims regarding yields are untrue, and that the reality is far slower with less production than many farms claim. Concomitantly, a second participant discussed that their yields continue to increase annually:

“Our yield is better than it was a year ago so definitely the quantity of what we can get out for our energy inputs is improving all of the time and will continue to improve.” (Entrepreneur)

This shows that current yields are likely to increase over time as the systems and science of CEA develop. Significant to this discussion, is not only how fast crops are grown, but what crops are grown. Most of our interviewees agreed that currently CEA primarily produces leafy greens and micro herbs, however, some are also venturing into other crops such as berries, mushrooms, soft fruits, and protein crops such as amaranth. While our research suggests that current CEA farms require development on their nutritional benefits, one entrepreneur did discuss that some of the leafy greens, such as spinach, can be used to produce high nutrition baby foods:

“One thing where this might be very interesting is baby foods. For example, you want plants that are--, they don't have any added chemicals. You want, for example, spinach that has a certain low level of nitrates. There's very specific needs for very consistent quality.” (Entrepreneur)

This shows that, although the current crop range is limited, there remain opportunities for nutritional produce to be grown, potentially tailored to groups with very specific nutritional needs. Overall, many of our participants felt that the current technology is not ready to produce heavier, higher calorie crops, such as potatoes:

“Yeah, the potatoes though are heavy, you know obviously they grow mass, so they've broken the shelves. I am sure the system could be optimised for heavier crops should it be a requirement. One system will not fit all and more bespoke designs could be found I am sure.” (Plant Scientist)

The lack of diverse crop range remains a challenge for CEA if it aims to tackle or address urban food poverty, as most of the current crop range does not have enough calories or nutrition to address this issue. This sentiment was confirmed by a participant who stated:

"The way they're financed through venture capital, that kind of thing, has tended to lead to them growing high turnover, high margin leafy greens, micro greens, baby leaf, that kind of thing. If it's going to have any impact on food poverty and those kind of--, and nutrition and really, really maximise that impact which I think it has enormous potential to do, you're going to have to find a way around some of those cost challenges." (Entrepreneur)

This quote confirms that crop range, nutritional content and price remain an issue if CEA is to address food poverty in urban areas. Figure 3 summarises the main considerations that emerged from this research regarding CEA’s ability to address food security which are: crop accessibility, crop type/range, crop quantity, and nutritional quality. Even with an increase in the efficiency of LEDs the energy conversion is still heavily stacked against producing crops (such as fruit, nuts, potatoes, cereals) that have a higher caloric content. Breeding could help to increase the light conversion efficiency but this will take time.

The use of CEA for seed development (e.g. potatoes) has the potential to provide for high health seed propagation and subsequent outdoor field production which might help to reduce associated health and economic impacts in countries with poor access to healthy crop seed.

4. Business Model

The business model was one of the key areas of focus during interviews with entrepreneurs. This is an area that was discussed less by plant scientists. Much like the topics already discussed, the business model is an equally complicated topic, as it relates to a multiplicity of factors.

These include:

- Start-up costs (funding and subsidies if available; risk and viability)
- Running costs (including employment, and energy costs)
- Branding and marketing
- Locating the farm (discussed in section 3.1)
- Ensuring the cost of produce is right for the consumer

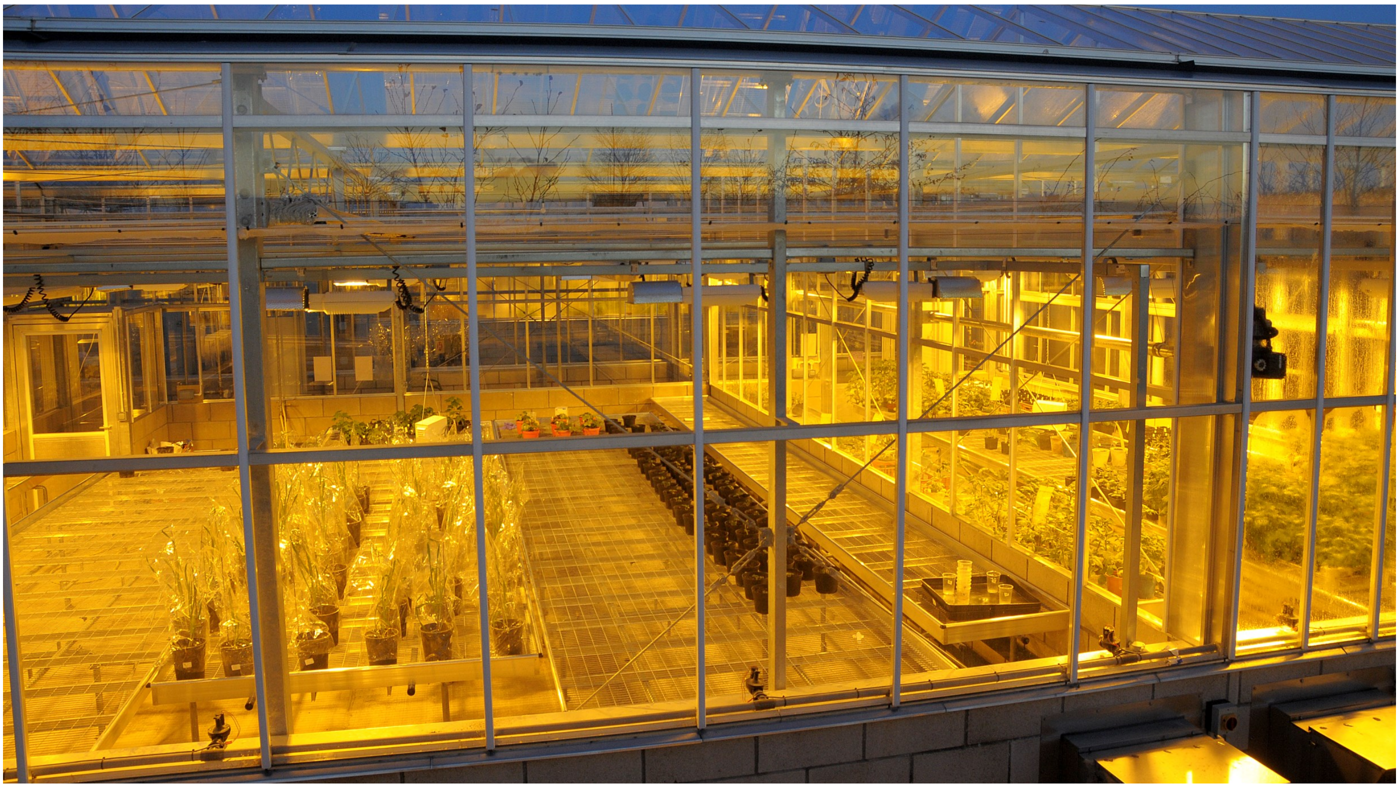
4.1 Start-up costs

Throughout the discourse, there is general agreement that CEA is an *'expensive'* form of agriculture. Our interviews included participants from small-scale farms of 1-3 employees through to discussions with multi-national farms and large-scale investors. This allowed us to understand the economics from a range of perspectives as the term *'expensive'* is subjective and varies according to the stakeholder group. From our initial literature review, we found that the cost of constructing a CEA farm is highly variable depending on the materials and technologies used. Banerjee and Adenauer (2014) performed a simulation which resulted in an estimated cost for a 37-storey vertical farm in Berlin. Their findings showed that this would cost €111 million (including site price), with equipment costing another €90 million. Zeidler et al.'s (2017) predicted that their purpose-built CEA farm in Bremen would cost €36 million. Despite considerable variation between these predictions, each of the purpose-built farm simulations would require significant investment.

The literature is yet to explore the economics of reducing construction costs through methods such as using existing structures as opposed to purpose-built sites, which is believed to reduce the capital cost significantly. Currently, a great deal of the literary discussion of the actual start-up cost of a CEA farm has been hypothetical. As such, we interviewed an investor of CEA who told us that there are a range of costs depending on the form of CEA farm:

"You can go with either something that will cost like twenty million plus with some of these larger systems, or you can start with something like a container farm, you know, start with one, that's probably let's say in the range of half a million dollars. Where IGS comes in is they are just about a million in terms of their starting, even slightly below that…" (Investor)

This costing is significantly less than the amount that the literature predicted further illustrating the large range in initial capital investment that new CEA farms are likely to face. However, the costs that are being discussed here may be considered as low to some, but



high to others:

“So, I would say that they are already actually quite affordable. I mean, obviously it's not peanuts, it's still a million dollars.” (Investor)

At the opposite end of the investment scale, we interviewed a small start-up who built their own farm in a space that they lease from a donor. They keep costs as low as possible by manufacturing their own equipment and by renting space in an existing building:

“All our systems are built in house just to save money. The cost of buying systems from companies in my opinion is pretty high for what you're getting and obviously they need to get mark up and whatnot… right at the start, initially, thinking alright, just do it on paper, how much is it going to cost us to build it, X, and how much is it going to cost to buy it, Y. The difference was so crazy so for us it just made sense to build it ourselves.” (Entrepreneur)

This shows that new entrepreneurs can find flexible options to bring the costs down if they have the skills and capabilities to do so. Renting units allows new entrepreneurs to try the business without having the initial risk of the large investment. This also allows entrepreneurs into the business who would otherwise be unable to find the initial investment. Although this is not the most common method of tenure in farming, it is emerging as a means of reducing the capital investment costs and bringing new entrants into the industry. A participant that we interviewed stated his organisation use this model and rent spaces to potential entrepreneurs who are interested in trying the technology:

“The main problem for many users is the lack of capital investment to buy the machine… in our research and development facility we have some space which could be rented by some customers.” (Plant Scientist)

While renting space and engineering the components oneself appears to be viable, this is typically for small-scale farms. The medium and large-scale farms will continue to seek large initial investment costs. This results in the majority of medium to large farms requiring large capital investment of at least half a million, either from outside sources (such as government grants/subsidies or independent investors) or the entrepreneur has their own capital to invest before the project can come to fruition. These large capital costs remain a barrier for new entrants wishing to start CEA and are combined with uncertainty around timescales for production for Return on Investment (RoI) even with the advantage of year round produce production. Estimates of <3 years for RoI are not uncommon and this depends on the ability to establish a good level of productivity.

“We talked about LED prices coming down, but it's still significantly more expensive than building a polytunnel. So that's undoubtedly the main barrier for entrants.” (Entrepreneur)

It should also be noted that extensive barriers to new entrants exist in traditional agriculture (Calo, A.et. al., 2021). A notable difference for new entrants to CEA is that less land is required, which may be advantageous to new entrepreneurs joining food production. Marshall et al (2020) discuss that the lack of access to public land for food growing is a barrier for urban community food growing projects.

4.2 Subsidies/support available: (risk/viability)

The issue of who can attract this large investment has been largely ignored in the literature on CEA, though Cohen, Reynolds and Sanghvi’s (2012) study on urban agriculture in New York City found that there are race- and class-based disparities in how urban farms received government support (see also Cohen and Reynolds, 2015). Some commercial farms had more financial resources and stronger relationships with government agencies, which meant that they are able to access hundreds of thousands of dollars in public funding. Smaller, minority- and community-led projects did not receive information on government support and had less experience of liaising with the government. As a result, these projects missed out on public funding and had to rely on grassroots fundraising instead. Guthman (2008) found similar inequalities. She argued that urban farming has typically been the domain of the white and the middle-class and that urban farms are often located in wealthier areas. As such, she argued that urban farming does little to alleviate the issues of food insecurity and food deserts in cities.

Most of our interviewees are already engaged in CEA farming, thus are likely aware of the subsidies and support available. One participant confirmed that they believe there is funding available for CEA, through subsidies and incentives, and that these will help those who want to get into the CEA business:

“There are funds, there's support available for people who are looking to get into this type of growing that makes that investment achievable.” (Investor)

A second participant noted that they are using a government incentive to help cover their employment costs. While this is not directly a funding avenue only open to CEA, it is a government funding source that is being used by the industry:

“Right now, we are using the government kick start scheme, so we've got an employee through them." (Entrepreneur)

However, not everyone will be aware of this support, or have the strong relationships with the investors, which could put them at a disadvantage regarding gaining investment. Investors should consider the structural barriers associated with urban farming. These barriers may be even higher in relation to CEA, given that it is more expensive than conventional urban farming.

We queried whether there is a role for the government to play regarding supporting CEA businesses. This gained a mixed response from participants as some believe that CEA should have the same subsidies as any other form of farming:

"Farming is farming, right? If you're going to have subsidy for farming you can't go that type of farming but not that one because that's just discrimination essentially, so I don't see any reason why we shouldn't be able to access some sort of subsidies because its food growing at the end of the day." (Entrepreneur)

However, concomitantly, a second participant responded by saying:

"But why? But why? Why should they? … Producing under lights through energy is less carbon? … It doesn't make sense, does it?" (Entrepreneur)

This illustrates that there remain polarised views in the industry regarding what form of government support they should receive. Further literature analysis disclosed that there are bureaucratic barriers to CEA regarding planning, governance, and policy (Ackerman et al., 2012; Thomaier, 2017). Some perceived a general lack of support from city governments, particularly regarding funding. Due to the initial risk that is associated with pioneering an innovative technology, it is possible that there will be support for the early adopters. Thus, it is likely that the amount of funding available will decrease as more CEA farms open (Goodman & Minner, 2019). A participant compared CEA to other technologies and the risk-cycle that they have undergone:

"The wind industry was supported to a point, where now there's virtually no support for turbines because that has helped by de-risking the initial stage to a point where efficiencies have improved, costs of components have come down, and people are able to invest themselves in those technologies." (Entrepreneur)

This participant anticipates a point where CEA is less risky, with reduced cost curves as the technology advances. It is possible that as the technology becomes more mainstream, this will help smaller entrepreneurs invest without taking on the same risks. However, being later into the industry could result in it being more difficult to find a niche segment of the market for their product. The current prohibitive costs combined with elevated risk may primarily attract wealthy large organisations into the market. Recently, we have seen large corporations, such as Walmart, buying into CEA. In this report, we seek to highlight the inequalities in the knowledge and relationships for sourcing available funding and to consider the disparities as the industry develops.

4.3 Running Costs: (Employment, Energy costs)

Advocates have promised employment opportunities as an economic benefit of CEA. However, from our literature review, we found that most of these claims are based on hypotheticals rather than factual evidence. Goodman and Minner (2019) discovered that in New York City, 150 people were employed in CEA across six companies, although the kinds of jobs available are less clear. Still, from our interviews we found that CEA could create many jobs, at different qualification levels:

"It's graduate jobs versus vocational jobs essentially." (Entrepreneur)

Several participants felt that high-skilled jobs would be available in engineering or software development:

"I think the types of people that we're going out to recruit now, it's not from your traditional agriculture families and universities. We've got people in our business that are mathematicians from Cambridge, so we need that skill set and knowledge. We need to understand agriculture isn't about pulling up your boots and standing in a field and getting all muddy." (Farmer & Entrepreneur)

Some participants felt that low-skilled jobs would also be available in packing and handling:

"If you establish these farms in that region you are providing opportunity for those people who lost their jobs because other industries were closed and they can again contribute to production, to management, to supply and so on." (Plant Scientist)

We also heard that CEA could reduce employment opportunities as CEA farms are likely to move in the direction of automation, thus not requiring many employees on site. However, it is significant to consider that many traditional farms are also using mechanisation, with auto-pickers and drones becoming more common place (Ingram et. al., 2022). As such it is not necessarily a straightforward comparison.

As previously mentioned, the yearly costs of CEA farms, including energy, water and labour, are very difficult to estimate and should be considered in terms of scale of production and ability to sell produce for profit. Subsidies or support might be an option to help producers transition to a profitable business but using taxpayers' money would depend on whether CEA is viewed as also providing wider public benefits, such as climate mitigation or enhanced food security. Banerjee and Adenauer's (2014) Berlin farm costs just over €8 million per year, whereas the Bremen farm costs just over €7 million per year. Zeidler et al (2017) predict the variable costs at nearly €5 million, highlighting how much uncertainty there is surrounding the yearly financial costs of CEA. Energy and labour are the two highest variable costs (Banerjee & Adenaeuer, 2014; Zeidler et al., 2017), although these could be reduced in the future, if there are advancements in LED lighting or if some jobs become automated (Al-Kodmany, 2018; Goodman & Minner, 2019). Similarly, several participants believed that automation could significantly reduce their labour costs:

"We can reduce our labour costs by 80%. It's a lot. We can spare a lot because with the full automation you don't need so much labour. That is why our system is more popular and more economical." (Plant Scientist)

Overall, the interviews support the literature that suggests that employment opportunities will be aimed towards the highly skilled, such as engineers and software developers (Al-Kodmany, 2018; Muller et al., 2017). Lower paid, manual jobs in packing and handling may be limited, and future automation may reduce these jobs even further (Goodman & Minner, 2019). Moreover, since different CEA projects have different labour requirements based on their locations and technologies, it is difficult to make generalisations about how many jobs CEA can create (Benis, Turan, Reinhard, & Ferrão, 2018).

4.4 Cost for consumer: (Social Justice)

A central theme which emerged in the interviews was the cost to the consumer. There are different markets that CEA can target depending on the aims of the business. Many interviewees felt that there is a cap to the amount that the public are willing to pay for produce, thus, for CEA to compete with the mainstream market, they would have to be competitive on price:

"They can't pay any more, particularly when their energy bills are going up." (Farmer & Entrepreneur)

It is important to consider the cost of food when designing the business plan, as many consumers will struggle to pay more. Participants who spoke about this topic typically fell into four groups regarding who they believe will buy CEA products; the general public at supermarkets and local shops, high-end clients such as wealthy customers and restaurants, a community-owned or supported CEA farm, or a hybrid model. This subsequent section will now consider each of these markets in turn.

General Public (Supermarkets, corner shops etc.)

A reoccurring sentiment which was discussed by many participants was the power that the big chain supermarkets hold over those who are trying to sell their produce. This was clearly stated by one participant who said:

"Supermarkets are huge buyers, and they hold all of the power." (Entrepreneur)

This is significant, as many participants perceive the power held by supermarkets is a barrier to entry. This is in addition to the fact that some supermarkets are starting to produce their own crops, thus limiting the space in the market for other smaller crop growers to join and sell to them. In a recent press-release, Walmart have stated that they have agreed to invest US$400 million in a partnership with Plenty as part of a strategic plan to utilise Plenty's technology to produce to Walmart retail stores (Walmart, 2022). Through this investment, Walmart will also join Plenty's board of directors (Walmart, 2022). Walmart is the first large U.S retailer to significantly invest in vertical farming (Walmart, 2022). Our participants discussed the fact that other supermarkets within the UK are considering bringing this technology into their stores. A plant scientist commented on this stating:

"I know supermarkets are talking about having something, vertical things, in the supermarket even so you can get your basil straight off under the lights" (Plant Scientist)

Participants noted the potential benefits to food being grown in the supermarket, including, that you could pick it directly, and not have to wash the produce before sale, and that it would reduce the distance travelled. Each of these could save costs, which may be reflected in the price. The primary concern remaining here, is if the supermarkets are growing all their own CEA produce, will they dominate this market and not leave space for smaller growers and businesses to flourish? However, a potential positive of the supermarkets investing in CEA is that the overall cost of construction is likely to come down, which would help fund the development and advancement of the technology. This could, in turn, reduce the initial investment costs and de-risk the technology, which would be a positive for the smaller entrepreneurs looking to join the market. However, when discussing the issue of large corporations joining the market with one of our participants, he discussed a recent court case in Europe where a large group tried to patent an idea regarding the root zone of CEA crops. This shows there are those who would keep the technology to themselves, thus would not help to reduce costs for smaller organisations. The patent was contested by other organisations as it would result in paying royalties, which they felt is negative for the industry. On the other end of this scale, a second participant discussed that they are part of UK Urban Agritech collective (UKUAT), which is a consortium that share their CEA development experience to help one another to succeed.

It is too early to tell if the power held by the supermarkets will dominate the industry, but it is right to remain cautious of domination. Retailers may have an ability to dictate and control the direction of the future CEA market through their high capital investments and buying power. In this instance, smaller producers may have to find a niche in the market, which may not find them selling to the public, which was often their goal. Many of our interviewees have ethical reasons for joining the CEA community and are driven by passion to help alleviate food insecurity and improve nutrition, thus, may see the public as the market that they want to produce for. It is significant to mention that supermarkets are often located where consumers need cars, thus, do not necessarily address the problem of food deserts.

High-end market

A second main market discussed was to sell CEA produce to restaurants, specialist shops/markets or high-end shops. In this regard, the sellers consider their produce as a niche item which they can sell for a high value. Participants discussed that CEA fruit and vegetables are often high quality, and that there are those who are willing to pay for quality. Two separate interviewees spoke of a strawberry which is being sold for $50 per kilo, which they believe has a market that

are willing to buy it:

"There is a strawberry variety from Japan, you can buy it in New York for fifty dollars a kilo. Fifty dollars." (Plant Scientist)

This shows that there is a market for high quality, high price CEA produce. This is a particular gap in the market, as $50/kilo of strawberry is significantly more than others. A second participant discussed that because the basil they make is so delicious, it means that the meals that are made from their basil are 'incomparable':

"The pesto is incomparable that we produce from these crops compared to the basil that you buy in different stores because it is just tastier, the smell is nicer, and you have a different feeling." (Plant Scientist)

Between the various discussions with the interviewees, it became apparent that many believe there is a space in the market for this high price, high quality produce. This is contrary to the market that much of the CEA literature claims the technology will address, as producing $50/kilo strawberries will not work to address food security. In this instance, CEA would have the potential to increase the gap between food inequalities and could even drive up the price of produce through introducing such high-cost items into the market. Nevertheless, high quality produce that is healthy and nutritious is important, and if CEA has the potential to produce high quality crops, many will feel there is space for that in the market. Each of these benefits and challenges must be considered when looking at the potential for CEA in this realm.

Community market

A third market that was touched on by a couple of participants was the potential for community owned CEA farms. Urban gardens and farms have a history of helping communities by acting as sites of resistance, empowerment and education (Taylor & Lovell, 2014). These benefits may be particularly pronounced for marginalised communities (Eigenbrod & Gruda, 2014). However, most research on the social benefits of urban farming focus on small-scale community gardens, and while it is possible that some of these benefits may translate to commercial CEA farms, we should not assume that they all do (Benis et al., 2018). In a study of urban farms in New York City, Dimitri, Oberholtzer and Pressman (2016) found that most farms were profit-driven, but often incorporated social aspects into their objectives, such as community-building and education. Urban farms that attempt to combine financial profit with social objectives could therefore be considered a form of social entrepreneurship. Cohen, Reynolds and Sanghvi (2012) agreed, highlighting some of the educational programmes run by commercial CEA farms throughout New York. A policy expert that we spoke to discussed the potential for community models in CEA:

"Community locality-based models could work here, where if you said to people look, you put X amount of your food budget, £2 a week, £3 a week, whatever it is, your food budget into this, we'll top that up. And then you've got £5 a week worth of veg that you can get from this particular project, whether its wholly community owned, whether it's got community aspects to it. I'm not saying that these things are easy or straightforward to do, but it would be nice to explore them rather than say there's no way we can, you know, you've got to have simply a private model that sells to supermarkets and then that's all there is to it" (Food Policy NGO)

It is a possibility that some community groups will take up CEA, depending on access to suitable space, affordability, and skills. Community gardening has been shown to improve behaviours and eating habits thereby having social value beyond food production. In the example explained by the interviewee, this would be a financially

beneficial model for consumers as they would receive more produce than the value that they put in. This would be good for the community who use it, as they would acquire skills and get subsidised fruit and vegetables. A second interviewee discussed an example of a community farm in the Bronx, New York, and the value that it has brought to its community:

"There's some examples, like there's one in the Bronx in New York that is a relatively basic CEA farm, but they built it up and they had school kids coming in and everyone would take shifts on the farm shift and there's such positive changes around it. So, I think in urban centres, CEA both grows food but it also, if done correctly, can connect people to their food as well, bring communities together which I think definitely is positive change." (Entrepreneur)

However, many communities are unaware of what CEA is. Success for CEA will be dependent upon the perception of different groups of the public, as consumers may perceive it as futuristic and unnatural to grow fruit and vegetables in indoor factories. A report by Coyle and Ellison (2017) found that members of the public rated vertically farmed lettuce as significantly less natural and significantly less likely to be purchased by the average consumer than other alternatives. One of the scientists we interviewed spoke about the fact that there is a need to educate people about CEA food, as it is the same seeds, just grown within optimal conditions. Without this education, consumers may not understand, and attach negative connotations to this produce:

"This is an education of people; this is a very big problem**"** (Plant Scientist)

A primary issue for community CEA is regarding the start-up and running costs. These resultantly mean that most farms are more likely to be profit-oriented, though there is some evidence to suggest that social benefits related to community and education may accompany these. Participants discussed the importance of incorporating school visits and education into their business model to reach out to the community in which their farm is located. A farm such as this could be primarily community focused, but it still has the potential to have a profit driven element that sells to the mass market, which brings us to the fourth main option discussed by participants, they hybrid model.

Hybrid

A final market that emerged from the interviews is the option to take the CEA farm in separate directions. This was discussed in different ways either:

- Part CEA and part traditional agriculture, where the existing routes to market and distribution are there, but they add a CEA facility to their portfolio
- Part CEA for high end clients with specialist produce, part CEA for the mass market
- Community and education farm, but with some profit-driven sales
- Crops grown part in CEA system and part in field

One participant summed up the potential to take your farm in two directions by stating:

"One of the advantages potentially of CEA is that you could do both because you could have ninety per cent of your facility growing your standard leafy greens day in, day out, and because you can have complete control over the individual crops and individual trays, you could have a small portion of your facility doing something completely different. So, you could take your business in two different directions if you wanted to." (Entrepreneur)

Scientists that we interviewed discussed the potential for hybrid growing, where crops are propagated in a controlled environment and brought to the field after. CEA would have a beneficial impact on food systems by enhancing UK capacity to assist different stages of soft fruit production, thereby displacing soft fruit growers' reliance on imported propagation material. It is likely that many farms in the future will incorporate this form of hybrid growing to get the most out of their field. The development of this route to commercialisation also comes with the outcome of positioning CEA/VF as part of the farming continuum and not a binary approach of CEA/VF or field production.

5. External Factors

5.1 Covid, Brexit, Climate change and Geo-Politics

Our literature review found that little research has been conducted on the economic impact of COVID-19 and Brexit on CEA. The Covid-19 crisis revealed the fragility of food supply chains (Rivington et. al., 2021) and illustrated the speed at which systems can collapse (Alraouf, 2021). Competition around who got essential supplies such as masks, gloves and sanitiser were evident, and this extended to other major resources such as food and energy (Alraouf, 2021). In 2021, COVID-19 and Brexit led to a shortage of HGV drivers in the UK, which disrupted the movement of products along supply chains. Several participants felt that COVID-19 and Brexit may have increased consumer awareness of food miles and sustainability and therefore demand for fresh and local produce:

"In that first initial period when we were just getting things built up, we were doing a lot of local deliveries and meeting people that had been affected by COVID, businesses as well that had been affected by COVID, and a lot of them were pretty enthusiastic about the local produce and they were loving the microgreens as well. And I think in general, yeah, probably people started thinking more about food and where it comes from and food miles, things like that, properly starting to question where that's coming from." (Entrepreneur)

Some participants felt that the disruption of Covid-19 and Brexit could have also pushed the UK government to take greater action to address our current food system's vulnerability to climate change:

"Yeah, I mean [sighs] obviously I don't want to say they're a good thing but the silver lining to COVID and to Brexit to some extent as well has been the UK, the governments, the devolved governments as well, have really been forced to take a long hard look, for want of a better term, root, and branch, at our policy environment. We're coming out of the common agricultural policy, all this stuff, the shortages, the difficulties, the long supply chains, the vulnerabilities, it has forced us to look at those things. And so, you look at something like CEA with the short supply chains and the potential sustainability claims and all those kinds of things and it does--, it should support the kind of goals that the governments are working towards or should be working towards." (Entrepreneur)

One participant also revealed that the UK governments support to small businesses in the form of grants during the pandemic helped them overcome some of the economic challenges of CEA:

"And then we started it and then moved into a unit and then four days later COVID started so that was kind of crazy...It was kind of nuts, but it actually worked out pretty well for us. Like we'd just started the company and then COVID hit and then all companies got a ten-thousand-pound grant, so that was like wow, ok." (Entrepreneur)

Overall, although COVID-19 and Brexit could increase people's interest in sustainable food systems like CEA, it is still too early to determine the long-term impact COVID-19 and Brexit will have on the direction of CEA.

Since conducting our interviews, recent Geo-political issues have emerged again exposing the fragility of food systems. Fertiliser prices are reaching all time highs, and the costs of fuel is soaring globally (Ladgrove and Hughes, 2022). This is both advantageous and detrimental for CEA, as the systems use less inputs such as fertiliser and pesticides, however, do require energy input.

5.2 Global Context

Much of the literature focuses on CEA in a developed world context, and in temperate climates, reflecting the wider upswing in agritech investment over the last 10 years. But there is potential for CEA to offer produtivity solutions in developing countries and more extreme climates. These countries may be reliant on costly imported food, facing rising population growth and urbanisation, and be more vulnerable to the effects of climate change (Kagan & Riemenschneider, 2018; McCartney & Lefsrud, 2018). As Hamilton et al. (2014) highlighted, urban agriculture already plays a significant role in delivering food security in many parts of the developing world.

However, there are certain barriers to using CEA in the developing world. The costs of constructing and maintaining a CEA farm are often prohibitive, making CEA a less viable prospect, especially since developing countries often struggle to attract investment (Kagan & Riemenschneider, 2018). There may also be technological barriers to using CEA in more extreme climates. Climates that experience extreme heat, cold or aridness require a distinct set of technologies and may have higher energy usage, for example for cooling. They may also have access to renewable energy sources with the potential then to off-set the additional demand in energy (McCartney & Lefsrud, 2018).

In highly urbanised environments CEA has been specifically targeted as a potential technology to increase food self-sufficiency. Singapore, a tropical city in Asia, is making significant strides in vertical farming with substantial public and private investment in R&D through high-tech, high-yielding, land-limited farms in high-rise buildings despite a highly constrained urban environment where land scarcity is exacerbated by a complex regulatory land use framework (Wood et.al., 2020).

The possibility to use CEA in a different context was discussed by a small portion of our interviewees. Many reflected that this may be a helpful solution for areas that have a climate that is difficult to grow fresh fruit and vegetables, but also have the capital for investment, such as Dubai, Singapore, and UAE. One of our entrepreneur participants mentioned that they are involved in a project aiming to help Singapore become more self-reliant. They stated that:

"Singapore has got lots and lots of people and very little land. So, their interest is more of producing produce without needing the masses of landmass for it." (Entrepreneur)

A second participant discussed benefits to CEA in the Middle East, by discussing:

"In the Middle East where they are effectively importing their produce from California on an aeroplane, it absolutely makes sense because you've got a very expensive transport leg bringing product in because they can't grow it in their environments presently." (Farmer & Entrepreneur)

Introducing CEA in international contexts, such as the Middle East, has potential to advance the system as this is an area with demand for the technology, and the financial capital advance it. Organisations who are developing this technology can sell it internationally. In this context, CEA is answering a question in their food system, thus it may be more likely to flourish in this context. The second global context discussed by participants is the potential to increase food security in less developed countries, or in humanitarian emergencies.

"If you look at Africa, the soils, it's very fragile soils, in any way not as conducive to growing crops outdoors, so I think it is a good solution for a lot of geographies and countries, but obviously not everyone could come in right away and see this as something that they can plug into their economies because again, it does right now need a lot of energy supply that needs to be fairly reliable". (Investor)

While there is a clear need for more secure food supply in parts of Africa, there are also challenges for establishing CEA. The initial set up and running costs are still too high for many developing countries and there are also issues regarding infrastructure, such as access to energy and water, that would need attention for this to be successful. As such, if proponents of CEA want this technology to be adopted internationally, and not just in the developed world, there would need to be a greater focus on how to make CEA economically and technologically viable in countries with difficult growing conditions or with limited financial resources.

6. Future vision of participants

Existing literature on CEA has largely ignored the potential for how the technology could transform food supply chains and the agricultural industry. Technological advancements in agriculture and changing food consumption patterns have a history of disrupting food supply systems (Seto & Ramankutty, 2016), so it is possible that widespread adoption of CEA technologies could do the same. Existing CEA farms have partnered with both national supermarket chains and small local shops (Walter et al., 2020); as such, CEA could either exacerbate trends of nationalised food production, or prompt a shift towards more localised consumption patterns. CEA could also lead to more high-tech, industrialised agricultural production, which would affect employment opportunities and the structure of the industry, especially in countries where high percentages of the population work in agriculture (Muller et al., 2017). Therefore, we need more interdisciplinary research to understand the wider social implications of CEA (Gómez et al., 2019).

Through our interviews, we identified that interviewees' visions for the future fell into three main categories: optimistic, realistic, and critical/sceptical thoughts. The main characteristics of these categories are displayed through quotes in Table 2. They illustrate a contested vision for the future of CEA. Currently, it is too early to tell how it will emerge, or which forms will emerge in which contexts. It is important to consider the multiplicity of opinions on the topic while it is in its infancy and think of what future implications CEA could have on people and their communities.

Optimistic Comments:

Many of the interviewees are excited by the potential of the technology. They see that CEA is answering a question and filling a gap in the market. Many of the comments made reflect a belief that it is required due to the environmental impact of existing agriculture and other comments see the need to decrease our reliance on imported fruit and vegetables. This has been exacerbated by political and external factors, including Covid-19, Brexit and climate change. Participants commented that CEA has the potential to help with these problems, and thus, it is inevitable that it will become a large player in the food system at some point.

Realistic Comments:

Realistic comments see CEA fitting into the food system, but not as the primary method of growing. Participants often commented on its potential in quite specific ways. Scientists spoke about the potential to reduce crop disease and help with specific plant qualities. They discussed that the plant would propagate in the tower, before going out in the field. Thus one of the main future benefits of CEA would be to produce high health winter soft fruit propagules in the UK, preventing reliance on winter import of soft fruit propagules and reduce issues regarding associated soil, pests and diseases. Home production of propagules would impact food systems by reducing transport miles and reducing pathogen spread in infected soil/plant material. Many interviewees spoke about the hybrid model, where farms may have a vertical element and a field. They do not discuss CEA as taking over from field growing, but instead, complementing the overall food system. One interviewee expressing realist views discussed the need for intentional planning out of the infrastructure for it to best impact the social needs of the communities.

Critical and Sceptical Comments:

A small number of participants expressed concern for existing farmers, questioning what CEA will mean for them. CEA is likely to bring different players to the market, many of whom will be new to agriculture and are attracted by the new technology. This raises questions about it disturbing or displacing those currently growing and producing food. Through this discussion, participants commented that there is a danger that big businesses will dominate the market. This could see the wealthy big corporations controlling CEA, and not leaving space for smaller growers. One critical comment that we noted stated that, as it stands, CEA is still too niche to compete or be a real player in the food system but noted that this might change in time.

The future of CEA is therefore still uncertain. An important consideration that our interviews expose is the range of future scenarios that could happen. This highlights a need for consideration for those allocating resources as there are risks associated with large funding all going in the same direction. As this technology develops, thorough attention should be given to who is benefitting, and in what ways. In section 4.2 this report discussed the support and subsidies available and ensuring that these are distributed and available to a range of stakeholder groups. This is important if the CEA community wish to avoid a scenario where it is primarily owned by large corporations or wealthy individuals.

Table 1: Future vision of participants

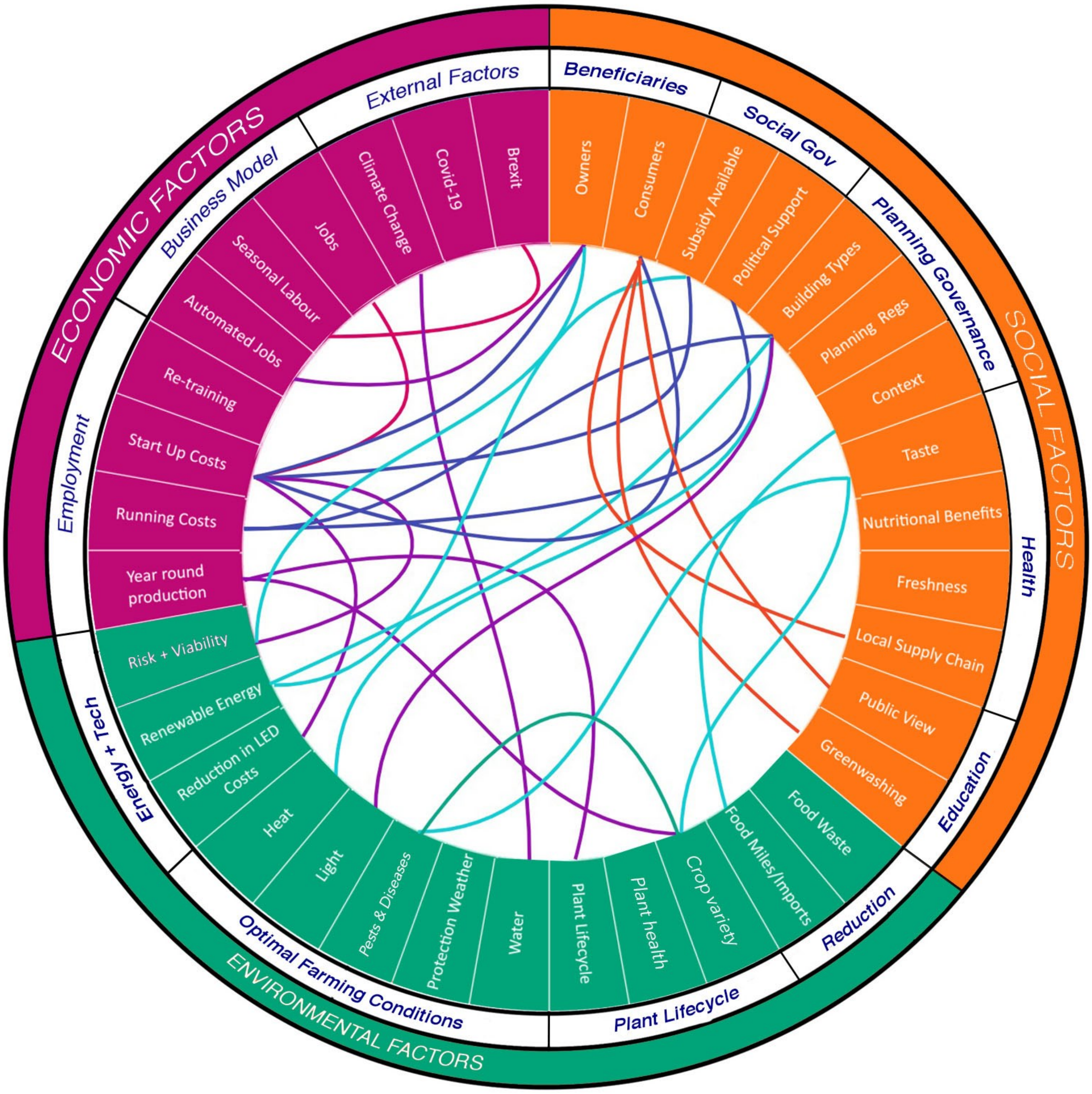
Optimists Characteristics	Realists Characteristics	Critics Characteristics
Believe there is a need for CEA: "the jury is no longer out there, it is a firmly needed solution." (Investor) Are excited: "It would make sense to produce more of them [fruit and veg] in this country. We might not have the land to do it so we might need vertical farming to help us to do it. And I think that's exciting." (Farmer) Are of the opinion there **is** a market: "I think there is a market for it because the quality and amount you can produce throughout the year is incomparable compared to anything else." (Plant Scientist)	Believe it should complement, not compete with existing British agriculture: "Vertical farming will not replace the traditional agriculture. We see this as complementation and working in parallel and supporting the existing agriculture techniques." (Plant Scientist) Should tie in with existing supply chains/ supermarkets: "the future of the industry is to have local hubs, so either built beside supermarket distribution or beside particular customers." (Entrepreneur) Should take the time to plan: "it would be good if government was interested in, not running the thing, but trying to steer and guide the thing so it serves public interest." (Food Policy NGO) See it as one part of the wider food system: "I think in terms of this I don't think there's any one solution really. It's got to be a lot of things combined together, a lot of change to all complement each other." (Entrepreneur) See it as part of the plant life cycle: "I don't think beginning to end kind of farming in the tower…" (Plant Scientist) See it answering an international question : "In the Middle East where they are effectively importing their produce from California on an aeroplane, it absolutely makes sense." (Farmer & Entrepreneur)	Are concerned for existing agriculture: "If the industry got to a stage where you could build a tower very cheaply and you could grow strawberries very cheaply and you could harvest them very cheaply, what does that mean for traditional strawberry farmers?" (Entrepreneur) Are concerned about big businesses dominating: "I personally have my suspicions that some of those are...yeah, vehicles for corporatisation essentially. And there is a danger of that happening I suppose." (Entrepreneur) Maintain that it is still too niche: "Presently. And I'm not saying in twenty years' time it won't have moved on exponentially and maybe the field should be scared, but as it sits today it's still in that niche." (Farmer & Entrepreneur) Concerned for farmers: "think it would be an absolute travesty for farmers not to be involved and for them to be able to bring their expertise to it … but they must be able to receive some of the benefit of this as well." (Farmer)

7. Conclusion

The plurality of opinions and factors that contribute to discourses of CEA are extensive. This remains a complex, multifaceted topic with numerous intersecting and overlapping benefits and challenges. This report has tried to clarify these discourses by listening to and reporting on the diverse range of views, whilst critically analysing the claims. Here, we have combined a comprehensive literature review with in-depth interviews with knowledgeable experts in the field. Through this amalgamation of sources that are rooted in both the theory and practice, we conclude that there is no single clear discursive narrative on the role for CEA in sustainable future food systems. Figure 4 aims to illustrate the plurality of factors that impact CEA, and map where the connections, contradictions and overlaps are. This shows the links that are made in the discussions and the complexity of the topic.

Environmental Impact:

A clear discussion point in both our interviews and the literature is around the environmental impact of CEA. Again, there are a pletho-



Key

- Interconnected social factors
- Interconnected economic factors
- Interconnected environmental factors
- Interconnected economic-environmental factors
- Interconnected socio-environmental factors
- Interconnected socio-economic factors

Figure 4: Deconstructing the discourse: plurality of interconnected indicators of CEA.

ra of interconnected factors that impact the environmental effects of different forms of CEA. Figure 2 illustrates both the positive and negative factors, showing the spectrum of views on the topic. More research needs to be carried out to evaluate the environmental impact of different kinds of CEA, and the potential for different systems to contribute to more sustainable food production, in which places and under what conditions. While CEA may be associated with fewer food miles and less water usage, this argument must be balanced by a consideration of the energy inputs required. These energy inputs can be reduced through advancements in LED technology, plant breeding to increase light use efficiency, and use of renewable energy. This report has therefore attempted to summarise and contrast various perspectives regarding the environmental impact and potential of CEA from both discourse and empirical evidence.

Food Insecurity:

The emerging technology of controlled environment agriculture has been promoted as a potential solution to food insecurity and urban food deserts. This was discussed as one of the primary drivers for being involved in CEA by many of our interviewees. These are significant issues, which disproportionately affect those on low incomes or who have difficulty accessing a healthy diet. While advocates of CEA discuss its potential to help alleviate some challenges of food insecurity, many remain cautious about its limits in this regard. However, it may be able to contribute to the wider food system to provide healthy food on a more local level. A concern was raised regarding the crop range. Currently, most CEA farms produce leafy greens and micro-herbs, which although high in some essential vitamins, minerals and contribute to recommended dietary intake of fruit and vegetables, are relatively low in calories and proteins. Providing a range of healthy and affordable food remain challenges for CEA to be able to address food insecurity. We also consider the price of CEA produce, discussing that many consumers are likely to either be unable or unwilling to pay the kind of prices that CEA produce will retail for.

Locating CEA:

To make the most of the benefits of CEA, attention is required regarding where to locate farms. Through our research, we concluded that there are numerous benefits to siting a farm at the end of the supply chain, be that urban, island or rural. We also interrogated many of the challenges around this, including the availability of suitable, affordable space, infrastructure, and planning regulations. Locating production close to consumers may also provide social benefits, such as community engagement and education, which are shown to improve diet behaviours.

Business Model:

A central theme that emerged for the entrepreneurs and investor that we interviewed was regarding the business model. Here, they discussed the costs, branding, marketing, location of the farm and the target market. The literature widely accepts that CEA is an expensive form of agriculture, however, in our interviews there were participants who felt that this was a reasonable investment for a business. They also spoke of the subsidies that are available. While there appear to be subsidies and support, we highlighted that there are disparities in knowledge of these funds which are available. This has been shown to result in a disadvantage in gaining investment due to these structural barriers. As such, consideration must be taken to ensure that CEA has a fair and equitable funding system for all.

Cost to Consumer:

A key discussion point for almost all interviewees was the cost for the consumer. Many discussed the current cost of living crisis and felt that many customers are not able to pay more for their food. However, they were also passionate about the supply of food contributing to a healthy diet. This is a difficult trade-off that many interviewees balanced, as they felt there is a need for healthy food, close to consumers, but at the right price. This will be difficult to achieve through CEA at this time, however, may become more possible in the future as the cost curves of CEA reduce. The power held by retailers was also touched on by several participants. We remain cautious of these big players in the food system who are now starting to fund CEA farms. They may dominate and dictate the market movements and costs, and control who joins and flourishes in the CEA community.

While many are passionate about supplying food to the public who require it, we found that many also believe that CEA is a niche product that can be sold to restaurants and specialist markets. Marketed based on its superior quality and taste fetches a higher price from wealthy consumers. This was illustrated through the discussion of a strawberry that currently sells for $50/kilo in America.

Community Engagement:

Section 4.4 discussed the potential for community enterprises and engagement. Here it is integral that the farm educates and empowers communities through their food. Community owned farms are known to have many benefits and seeking to make these financially viable could be hugely beneficial for communities with limited range and access to fresh food for climate or supply chain reasons.

There are many social benefits to a local CEA facility, but a barrier remains in the form of upfront capital and running costs. The final market that many participants dialogued about was hybrid. This was envisioned in several ways, all of which involve part CEA, and part field farming. There are many advantages to this form of growing as it reduces the initial risk and allows CEA to support the field, and vice versa.

External Factors:

Many external factors are currently having a significant effect on food systems, including Covid-19, Brexit, climate change and Geopolitical factors. We found limited research regarding the economic impact of Covid-19 on CEA. The Covid-19 pandemic revealed fragilities in global food supply chains, forcing governments to think more carefully about resilience and local food. This is an area that CEA may be able to address in part, as it can reduce reliance on external food chains.

Global impact:

Looking globally, there are potential benefits to CEA technology in areas that have extreme climates that must import their food and are often vulnerable to the effects of climate change. CEA could be beneficial in these contexts by providing independence and security. This is likely to occur in wealthy countries in the Middle East as they have the capital for the set up, but many question if this would be addressing problems in their food system. Participants also discussed the potential for CEA to be used in developing countries, or refugee camps. While smaller systems may have the potential to operate in such hostile circumstances, there remain challenges and barriers regarding the cost and available infrastructure. Nevertheless, these ideas should not be discarded without further investigation into their benefits.

Future Vision:

The final question we asked participants was where they expect CEA to go in the future. In general, participants views were divided into three main groups: optimistic, realistic, and critical. The optimists were often excited by the potential of new technologies and believed that there is a market and a need for it now. While they have ambitious claims, these narratives are still to be put into practice at any scale.

The realists see CEA becoming part of agricultural production as a hybrid component of farms, and a tie in with existing supply chains. Many of them feel that it will be used in the Middle East, and this will help the technology to develop and de-risk. Many of the realists cautioned the need to take time to plan the system and referenced countries (such as Norway) who have an excellent glasshouse industry for their food production.

Finally, the critics raised concerns about potential retail dominance driving CEA, pushing out more traditional forms of agriculture and sidelining farmers' knowledge. They maintain that as it stands, CEA is still too niche to attract the market that it requires.

While CEA is in its infancy, we remain cautiously curious about its potential impact on food systems. There are certainly many interesting potentials of this technology, but each of these potentials are balanced by other factors creating challenges and drawbacks. Trade-offs will need to be balanced while the technology advances to ensure that it serves the greatest potential to both consumers and businesses alike.

Priorities for Development

From this research we have developed a number of questions concerning the future development of total controlled environment agriculture and vertical farming:

- What is the range of crops that can productively be grown in vertical farms (VF) under controlled conditions? How does this range relate to dietary recommendations and cultural preferences?
- Can vertically-farmed produce lift food nutritional levels? And if so, for whom and where?
- Can TCEA technology be democratised, for example through subsidy or community sponsorship?
- What are the implications for food supply chains of introducing CEA produce?
- What are the particular advantages, barriers and benefits of developing CEA/VF for rural and/or other disadvantaged or marginalised communities? Is there a role for small scale VF in disaster management or population displacement for example?
- Will CEA/VF develop as a disruptive or additive technology? i.e. will VF technology integrate with existing systems or will it provide a novel form of production?
- How do we meet the energy demands of CEA/VF and best integrate with local renewable energy systems?

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Appendix 1. Methodology and analysis method

To explore and investigate the discourse around CEA, we used semi-structured interviews with twelve experts from a range of backgrounds and professions related to CEA. This allowed us to gather mixed perspectives and knowledge of the industry. Participants included entrepreneurs from small- and large-scale CEA farms, traditional farmers, and farmer union representatives, plant scientists, and investors in the technology. We used a purposeful sample to access a range of views on CEA, thus inviting both sceptics and optimists to interviews.

The interviews lasted 1-hour and were conducted online on Cisco WebEx. They were carried out by a team of researchers over a 4-month period in 2021-2022. Most participants were from Scotland, however, also included participants from England and North America. Interviews were semi-structured with open-ended questions guiding the interview. The interview protocol was used to systematically ensure interviewees were being asked the same questions whilst allowing flexibility to elicit the views and opinions of participants. The interview protocol encouraged participants to explore factors of CEA regarding its social, economic, and environmental impacts.

Anonymised interviews were transcribed by a third-party. The transcripts were manually analysed using Nvivo 11/12 software, taking a deductive approach focusing on the themes from the framework. The framework aims to provide a comprehensive set of themes, which emerged from a literature review of the current discourse of CEA, conducted prior to interviews. During the coding process, patterns emerged in the data, which have formed topics for this report. The interview protocol and thematic framework can be found in Appendix 2 and 3 respectfully.

The interview panel included

2 Plant scientists

5 CEA entrepreneurs (both technology entrepreneurs and growers)

3 Farmers/farmers union representatives (who may also use CEA in their farms, but also traditional agriculture)

1 Policy expert

1 Investor

Appendix 2. Interview Protocol

Questions for context

1. How would you briefly describe or define Controlled Environment Agriculture? Alt: **What do you understand by the term 'controlled environment agriculture'?**

Probe for ideas of what participant thinks CEA includes/excludes. What isn't CEA? E.g., polytunnels, greenhouses?

where they get their ideas/conception from,

what technologies are important in CEA,

how it differs from other forms of food growing technology.

2. **Briefly, to get some context, what is your role in relation to CEA?**

What is your rationale for working with or developing CEA?

3. When and why did you become involved?

Food systems questions

4. What are the issues or challenges with current food systems (that you think CEA might help to address)?

Prompt –E.g., impact on food poverty, food justice, food safety, healthy diets/nutrition, environmental degradation, waste, CO2 emissions etc.

At what scale (local/urban, regional systems…)

5. Why do these issues exist? (e.g., why is scale important, why is energy supply an issue, why is ownership interesting?)

6. How might CEA help to alleviate the issues you've talked about? Probe for **advantages** for whom – retailers, consumers, growers, food security, business model, etc.

Probe for possible technological **advantages** – more efficient use of space, light, energy, resources?

Probe for business model, food production advantages, energy usage, providing greater food security/safety/quality, science, and plant health

Probe for potential **disadvantages of CEA** in the form of costs, public acceptance of indoor grown food, restrictions to high value produce, high start-up costs, taking urban land away from other uses, issues of scale, owned by farmer/community vs capture by large business.

Technological **disadvantages** such as energy or resource use including life cycle of CEA inputs-outputs, scaling up.

7. **What do you think are the barriers to and drivers of CEA adoption? What might prevent CEA from addressing these issues?**

Prompt - Capital, crop types, technology, markets, food policy

What needs to happen for CEA to become established at scale?

Over what timescale will CEA develop? **Why?**

8. External and long-term impact factors: What impacts might things like climate change and Covid have on any of the above?

What direction do you think CEA is likely to take over the next decade? Is this the direction it 'should' take if it is to improve the food system as a whole? **Why?**

Thank participant for their time; leave them your contact details should they have any further thoughts; explain what will happen next:

Remind them that we'll analyse the anonymised transcripts and use the findings to construct systems models to represent the possible impact/influence of CEA on food systems. (Unable to progress the systems models currently).

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