CONTROLLED ENVIRONMENT AGRICULTURE AS A TOOL OF SUSTAINABLE INTENSIFICATION TO REDUCE FOOD INSECURITY

A Thesis

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ABSTRACT

It is well established that food production will need to increase by 70% to feed the world's population by 2050 (FAO, 2017) under a backdrop of declining land and natural resource availability. One way to meet our food needs is through sustainable intensification (SI), where agricultural yields are increased without adverse environmental impact or additional land use. However, most research into SI has been in open field growing systems. Controlled Environment Agriculture (CEA) may be another tool of SI that improves food security, especially in Low- and Middle-Income Countries (LMIC). CEA encompasses a variety of systems such as high tunnels, greenhouses, or vertical farms that take a technology-based approach to increase crop productivity, which is decoupled from the natural environment. This paper looked at the tradeoffs of CEA through literature review and life cycle sustainability assessments (LCSA) within the context of developed and developing countries.

The findings suggest that controlled environment agriculture is not a one size fits all model. CEA has been shown to increase water use efficiency, but at the expense of higher energy use. The choice of system needs to consider the tradeoffs between water, energy use, and the crop grown. While the U.S. has wide adoption of all CEA technologies with a focus on supplemental or sole source lighting, India has adopted more simplified versions of CEA, including polytunnels and plastic greenhouses with natural lighting and limited cooling. CEA can reduce poverty through job creation, thus indirectly supporting food security through increased income. However, due to higher production costs associated with greenhouse and plant factories, commercial farms continue to target high end retail. Without more widespread adoption and expansion of product offerings, CEA will have trouble meeting the dietary requirements of the world's growing population.

BIOGRAPHICAL SKETCH

Chantel Dixon grew up in the forests of Washington State. She developed a love of plants early while gardening with her grandmother and exploring the different ecosystems of the state with her family. She studied agricultural biotechnology at The Evergreen State College where she developed an interest in food security. Instead of going into agriculture after graduation, Chantel went into cancer research for the next 9 years.

Her career in cancer research and development started in 2013 at Presage Biologics, in Seattle, and lasted for the next six years until she moved to New York City. While at Presage, Chantel was taught everything from tissue culture to mouse handling. Her work with the team led to a published paper, furthering advances in Presage's technology. In New York, she worked at two companies, the Icahn School of Medicine at Mount Sinai and Cellectis Inc. Within this field she became an expert in study design, quantitative analysis, and collaborative teamwork. She also honed her management skills, making the transition from R&D to laboratory supervisor at Cellectis. She gained a deep understanding of working with multiple stakeholders, project management, and managing operations effectively.

However, her love of plants and passion for food security never wavered. Prior to moving to New York, in the summer of 2015, Chantel worked on an organic coffee farm in Kona, Hawaii. She learned about regenerative agriculture and agroforestry while she helped maintain the garden that provided much of the food for the interns. This love of growing food then lay dormant until the Covid-19 pandemic, when Chantel started looking into alternative forms of agriculture and discovered the Controlled Environment Agriculture program at Cornell University. In 2021, Chantel decided to leave her job at Cellectis Inc., and pursue her Master of Professional Studies at Cornell.

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LIST OF ABBREVIATIONS

CEA	Controlled environment agriculture
CED	Cumulative energy demand
DWC	Deep water culture
GH	Greenhouse
GWP	Global warming potential
LMIC	Low to middle income country
HIC	High income country
NFT	Nutrient film technique
PF	Plant factory
SDG	Sustainable development goals
SI	Sustainable intensification
TRWR	Total renewable water resources
UA	Urban agriculture
VPD	Vapor pressure deficit
WUE	Water use efficiency

INTRODUCTION

Overview of the state of worldwide agriculture

The Green Revolution marked a period of increased agricultural productivity due to new genetic research, technology transfer, and adoption of new cultivation methods. Between 1960 and 2000, agricultural output for all developing countries rose 208% for wheat, 109% for rice, 157% for maize, and 78% for potatoes (Pingali, 2012). However, the Green Revolution also relied on the use of pesticides and fertilizers, leading to land degradation all over the world (Armanda et al., 2019). Today, agriculture is currently responsible for about one-third of greenhouse gas (GHG) emissions contributing to climate change. Additionally, agriculture today accounts for approximately 70% of all freshwater use (IPCC, 2019). As the need for food, fiber, and fuel continues to increase, so too does the need for a continuous water supply, leading to unsustainable water practices. Beyond water, agricultural practices also have a great impact on food security and sustainability. As Pingali (2012) notes, low-income countries and emerging economies continue to rely on agricultural productivity as an engine of growth and hunger reduction. Furthermore, a growing middle class who can afford higher quality foods such as animal proteins, fruits, and vegetables are adding even more environmental pressure to an already strained food system with declining natural resources. Thus, food production will need to increase by 70% to feed the world's population by 2050 (FAO, 2017). There is a need for the agricultural sector to continue to adopt evolving technologies to sustain crop yields without further environmental degradation.

Overview of the impacts of climate change on agriculture

Current levels of global warming have increased Earth's average surface temperature by about 1 degree Celsius (1.8 degrees Fahrenheit), since the pre-industrial period and continues to by more than 0.2 degrees Celsius (0.36 degrees Fahrenheit) per decade (NASA, 2023). This increase has been associated with moderate risks from increased dryland water scarcity, soil erosion, vegetation loss, wildfire damage, permafrost thawing, coastal degradation, and crop yield decline (IPCC, 2019). Globally, 33 percent of the world's farmland is moderately to highly degraded (FAO, 2017, p. 32). All these issues lead to risks in food production systems and food security. The effects of climate change on agricultural production and livelihoods are expected to intensify over time with varying results across nations and even regions. So far, the gap between farm yields and potential yields reflects these constraints, with insufficient adoption of more productive technologies, a lack of market integration and gender inequalities in small-scale family farming being some of the most common (FAO, 2011b).

Overview of worldwide hunger today

The definition of "food security" is that all people, at all times, have physical and economic access to sufficient food to meet their dietary needs and food preferences for a productive and healthy life (World Bank, 2023). This definition is further divided into four main pillars including availability, access, utilization, and stability. Availability is the immediate supply of food, set by agricultural output and trade. Access pertains to the economic and physical ability to obtain food. Food may be available, but if the individual cannot afford to purchase or lives too far from the site of available food, then it will be difficult for them to access. Food utilization is understood as the how the body processes the nutrients of the food consumed. It could also be thought of as the nutritional status of food and the individual. Stability is all three pillars over time. Increasing climate variability affects crop production and raises food prices, contributing to the destabilization of food security for many populations, especially those in extreme poverty.

In 2015, all 193 United Nations member countries signed on to 17 Sustainable Development Goals (SDGs) of the World Bank Group to guide global action for reducing extreme poverty by 2030. The second goal included ending hunger, achieving food security, improving nutrition, and promoting sustainable agriculture. After remaining relatively unchanged since the signing of these SDG's, the prevalence of undernourishment jumped from 8% in 2019 to around 9.8% in 2021 (FAO, IFAD, UNICEF, WFP and WHO, 2022). It is estimated that 2.31 billion people were moderately or severely food insecure in 2021, which meant the inability to regularly eat a healthy, nutritious diet. Much of the increase related to food insecurity can be attributed to increased price of nutritious food, leading to decreased access. In India, the average cost of a nutritious diet in 2020 in US dollars was $2.97 per day compared to $3.38 per day in America. However, in India 70.5%, or 973.3 million people, could not afford this versus only 1.5% or 4.5 million people in America (FAO, IFAD, UNICEF, WFP and WHO, 2022).

Overview of urbanization and creation of food sheds

As the United Nation reports, "55% of the world's population lives in urban areas, a proportion that is expected to increase to 68% by 2050 (2018)." Due to rapid urbanization, there is increasing competition for agricultural land and natural resources. Since 2014, urban sprawl has consumed approximately 1.9 million acres of farmland per year (Agfunder, 2023). This competition has led to crop production farther from the areas that they serve and a more globalized food system. The globalization of the food system has many benefits, including supply chains that provide consumers with year-round access to foods they would otherwise not have in their regions. However, as the distance between producer and consumer expands, it has also contributed to loss of quality, and increased greenhouse gas emissions through transport. It is estimated that fresh produce currently travels over 1,500 miles from farm to consumer in the United States (Hill, 2008).

Even worse, an extensive study by Li et al. (2022) found that global food-miles corresponded to about 3.0 $GtCO_2e$, or 19% of the total food system emissions when accounting for land use change, production, and transport. For vegetable and fruit consumption, global transport was associated with almost twice the amount of greenhouse gases released during their production.

In contrast to the global production system are food sheds, defined as "the geographical area between where food is produced and where that food is consumed," like a watershed (Hahn, 2013). Local food sheds, such as community supported agriculture (CSA) and farmers markets have been gaining popularity because the food produced travels less than 100 miles from producer to end user. Urban and peri-urban (the zone between urban and rural areas, usually on the outer limits of urban centers) agriculture using controlled environment agriculture (CEA) makes it possible to produce fresh, nutritious food with low carbon and water footprints, while conserving land, reducing emissions and waste, and providing healthy, affordable, accessible food to its residents even closer to these urban centers.

Overview of controlled environment agriculture

Controlled Environment Agriculture (CEA) is an intensive, technology-based form of agriculture. CEA allows growers to predict plant responses to their environment, increase production efficiency, optimize plant yield, and improve product quality by capitalizing on advanced horticultural techniques and innovations in technology (Gomez et al., 2019). Greenhouses (GHs) are more enclosed structures, which provide more opportunity for control over environmental variables by employing heating, lighting, shading, ventilation, and cooling. Greenhouses can utilize hydroponics, aeroponics, or aquaponics. Plant factories (PF), or PFALs (PFs with artificial lighting), sometimes called vertical farms, are multi-layer production facilities in which offer complete control over the environmental parameters such as humidity, light, temperature, and CO_2 at the cost of higher energy consumption and higher initial investment (Eaton et al., 2023). CEA has "an advantage over conventional farming methods in that production processes can be largely separated from the natural environment; thus, production is less reliant on environmental conditions…" (Cowan, 2022). Table 1 defines common structures, growing techniques, and considerations one might make when starting a new project.

Hydroponics is the umbrella term used in CEA and means a soilless plant production where the root-zone is carefully managed to meet plant water and nutrient requirements. Within hydroponics are methods such as deep-water culture, nutrient film technique, and aggregate or soilless production. Deep water culture (DWC) is a technique where plants sit on rafts while the roots are constantly submerged in a continuously aerated, nutrient-rich solution. The solution is typically 9 to 12 inches deep. Nutrient film technique (NFT) is a highly efficient system that uses a thin film of nutrient solution that is pumped through channels or gutters to constantly circulate over the plant roots. Aggregate production consists of growing crops in bagged substrates (e.g., rockwool or coconut coir slabs) or containers (e.g., Dutch/Bato buckets) with the nutrient solution applied using drip emitters (Gomez et al., 2019; Wilkinson et al., 2020). Both NFT and DWC systems are commonly used for short term, non-fruiting crops such as leafy greens and herbs, while long-term crops such as tomato, cucumber, eggplant, pepper, and strawberry use aggregate production. Aeroponics is used when plant roots are kept hanging in the air and the nutrients are provided to the plant using sprays through nozzles, either continuously or after fixed intervals. Aquaponics combines aquaculture, or the rearing of fish, with hydroponics where the fish effluent is used as fertilizer for the plants, potentially reducing input costs. There is also research and commercial production of melons, microgreens, and fodder for livestock in this production system.

Many of these production systems reside in urban or peri-urban areas. Table 2 provides more information on typical growing conditions in a CEA environment. One of the main benefits of CEA with hydroponics is increased water use efficiency. In these systems, excess irrigation water is typically captured, filtered, and reused. Instead of overhead spraying used in conventional agriculture, drip emitters in aggregate production can precisely deliver the right amount of water the plant needs to grow, further conserving water.

The explosion of new growing techniques in CEA has contributed to a rise of new agribusiness ventures all over the world. Previous studies have historically looked at CEA systems concentrated in the U.S.A. and Europe. These countries were the first to implement CEA due to the need to produce food in the winter months. However, as the industry grows, so do the locations of these farms. It is estimated that the India hydroponics market is expected to grow at a CAGR of 13.5% from 2022-2029 (Data Intelligence, 2022) versus only 1.4% in the U.S. for the same period (Curran, 2023). This data indicates that interest in and investment for hydroponics is unlikely to stay concentrated in high income, Northern countries like the U.S. or Spain, Italy, and the Netherlands in Europe. Impact studies are crucially needed to assess the sustainability of CEA in countries with largely different climates than that of the U.S or Europe. The objective of this paper is to explore the potential for CEA in a developed vs. a developing country, using America and India as case studies through a literature review as well as an environmental and social life cycle assessment.

Table 1. CEA facility types and considerations

TYPE OF FACILITY	METHODS USED	CONSIDERATIONS
POLY TUNNEL	Soil production Soilless substrate (rockwool slabs; coco coir; peat) Hydroponics Deep water culture Nutrient film technique Ebb and flow	Modified growing environment can extend growing season; use of natural light; protection from heavy rains keeping out pests and disease; limited environmental control; is lowest cost
GREENHOUSE	Soil production Soilless substrate (rockwool slabs; coco coir; peat) Hydroponics Deep water culture Nutrient film technique Ebb and flow Aquaponics	Year-round production possible; temperature and humidity can be actively controlled through heating, venting, and evaporative cooling; use of natural light and supplemental light; protection from heavy rains; keeps out pests and disease
VERTICAL FARM	Hydroponics Nutrient film technique Aeroponics	Absence of sunlight, i.e., all electrical lighting; complete environmental control possible through lighting and HVAC; pest and disease management; energy inputs; highest cost to start and manage

Table 2. Common crops produced and typical growing conditions in CEA.

	Temperature (DT/NT)	**Relative Humidity**	**Pollination required**	**Photo-period**	**CO_2 Concentration**	**Cultivation Period (Days)**
Lettuce	25 °C / 22 °C	60–70%	No	18+ h	800–1200 ppm	30
Tomatoes	25 °C / 18 °C	75%–85% vegetative; 65%–75% for flowering	Yes	18 h	1000 ppm	90+
Herbs	20 °C /15 °C	70–80%	No	varies	800–1200 ppm	50 – 90 variety dependent
Micro-greens	21 °C/ 17 °C	80%	No	16+ h	500–800 ppm	7 - 21 variety dependent
Cucumbers	25 °C/ 21 °C	75–80%	No, but can improve yields depending on cultivar	16+ h	450–600 ppm	55–65
Eggplants	25 °C / 18 °C	75%–85% vegetative; 65%–75% for flowering	No, but improves yields	16+ h	1000 ppm	90+
Peppers	21 °C/17 °C	55–65%	Yes	18 h	450–500 ppm	120+
Strawberries	30 °C /15 °C	65% (day); 100% (night)	Yes	16+ h	1000 ppm	90

(DT=Daytime temperature; NT = Nighttime temperature)

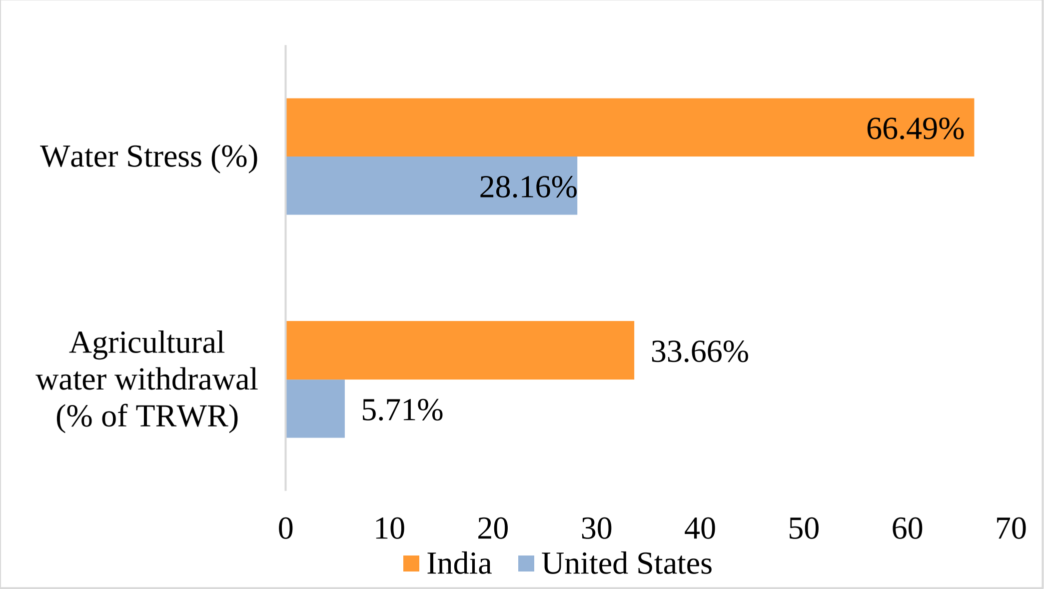
CONTRIBUTIONS OF CEA TO SUSTAINABLE INTENSIFICATION

Innovations in agriculture have become more sophisticated in the last decade, from precision water management to digital products that support sensible use of pesticides and fertilizers. This abundance of technology has enabled farmers to increase productivity without increasing their labor. However, crop and post-harvest loss is still a major concern, especially in low-to middle income countries. Production yields have not kept up with a rising global population, mainly because of higher incidences of extreme weather.

Water availability has also become a key challenge to support plant growth. This is due to extreme weather events, as well as increasing human population leading to increased water use. In all parts of the world, the pressure on water resources continues to rise in varying levels. The level of water stress, as seen in table 1, indicates the ratio between total freshwater withdrawn against total renewable freshwater resources. Water stress is when the demand for water exceeds its supply. In India total water withdrawal for agriculture was 36% of the total available water and the availability of per capita water is expected to decrease to 1335 m^3/year by 2025 (FAO, 2015). India’s dependence on an increasingly erratic monsoon season for its water requirements has made India 66% water stressed compared to the United States at 28%. There are also several challenges for water resource management including neglected irrigation reservoirs; extensive pollution of water bodies; and land degradation caused by flood, water, and wind erosion. In America, pressure on water resources is not as dire. However, climate change is already increasing water demand while shrinking supply and water availability can impact some areas used in intensive agriculture.

CEA can address this challenge in several ways. First, one of the best advantages CEA has over conventional agriculture is its ability to reduce water usage. Growers can minimize water waste and ensure water is used efficiently through careful monitoring of moisture levels and precise water application. Second, CEA systems can recirculate and reuse water. Finally, CEA systems can incorporate water efficient technologies, such as drip irrigation, which delivers water directly to plant roots, minimizing evaporation and runoff. Evapotranspiration, or the movement of water to the atmosphere through evaporation and plant transpiration, is significantly reduced in contained structures. In many hydroponic systems, water use can be reduced 90% compared to traditional farming methods (Cowan et al., 2022). CEA offers a promising solution to current and future water scarcity challenges faced by agriculture.

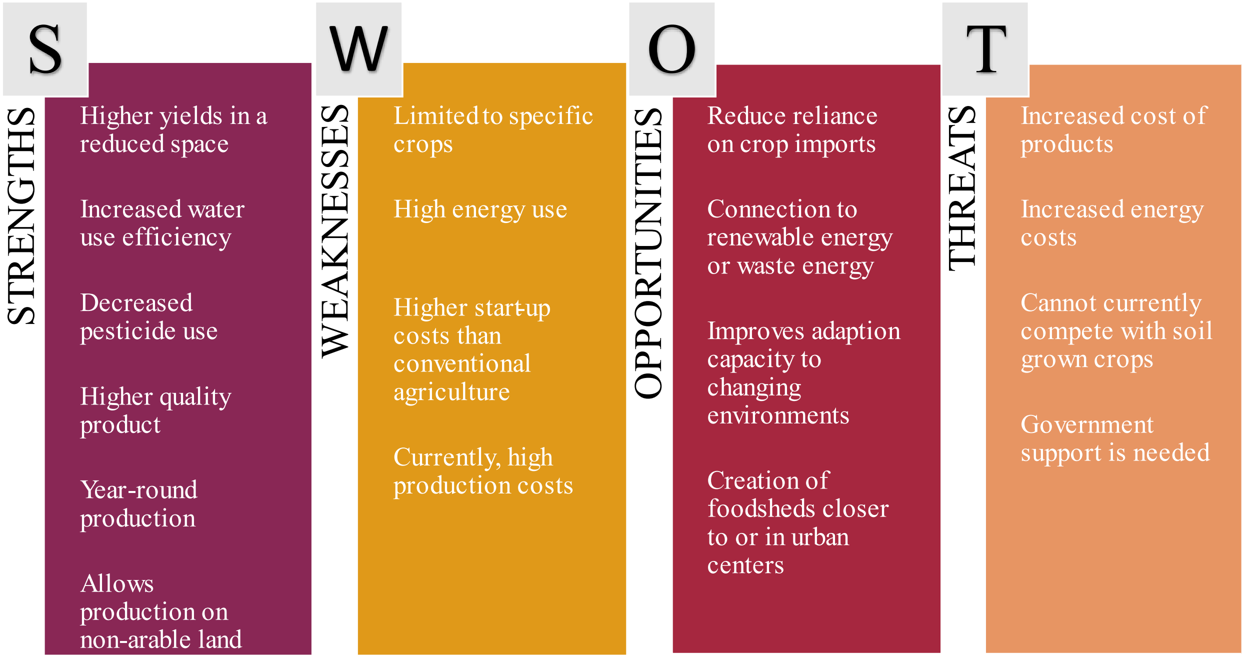
Figure 1. Pressure on total renewable water resources.



SWOT Analysis

To better understand CEA's contribution to sustainable intensification, an analysis was performed of its strengths, weakness, opportunities, and threats, (SWOT, figure 2). Many of the current strengths of CEA are inherent to its design. The ability to control the growing environment and be protected from environmental pressures makes CEA a solution to growing more with less for year-round production. Many CEA producers have also touted the benefit of higher yields from a smaller space. As Zhou et al., (2021) noted, “The land area used for greenhouse production worldwide exceeds 470,000 ha with yields up to ca. 10 times higher per unit area compared to field production.” Because crops are grown in a controlled environment, water use efficiency is increased while pesticide use is decreased. This also allows for CEA operations to grow food in areas that would otherwise not support crops, such as non-arable land or in cities.

Figure 2. SWOT analysis of controlled environment agriculture.



S
STRENGTHS
- Higher yields in a reduced space
- Increased water use efficiency
- Decreased pesticide use
- Higher quality product
- Year-round production
- Allows production on non-arable land

W
WEAKNESSES
- Limited to specific crops
- High energy use
- Higher start-up costs than conventional agriculture
- Currently, high production costs

O
OPPORTUNITIES
- Reduce reliance on crop imports
- Connection to renewable energy or waste energy
- Improves adaption capacity to changing environments
- Creation of foodsheds closer to or in urban centers

T
THREATS
- Increased cost of products
- Increased energy costs
- Cannot currently compete with soil grown crops
- Government support is needed

The weaknesses and threats of CEA mainly surround costs and energy use (potential carbon emissions). Controlled environment agriculture is a technological innovation as much as agricultural one. An increase in technology requires an increase in energy and thus an increase in costs. As Engler et al (2021) notes, “Two of the major issues for CEA facilities to date include high operating costs preventing farmers from turning a profit, and typically high carbon footprints per crop for high-tech CEA which hinder government efforts to mitigate carbon emissions.” The high energy needs of CEA limits crop choices to a few high yielding crops like lettuce and tomatoes. Until these costs are reduced, growers will not be able to compete with soil grown counterparts that are cheaper to produce. Further CEA is not currently economically practical for staple crops such as cereals and legumes.

The opportunities CEA presents could mitigate some of the weaknesses and threats. For instance, the ability to grow food closer to the consumer may reduce countries' reliance on imports. Furthermore, these systems could create foodsheds to combat food deserts. Creation of CEA systems can also help communities adapt better to climate change because food production is decoupled from the external environment. Environmental sustainability of CEA systems depends largely on the availability of low or zero-carbon energy. (Cowan et al, 2022). With proper planning, new construction could connect to waste energy streams from other operations, such as biogas from anaerobic digestion of organic waste. In this way, CEA has the potential to locally produce food year-round, ensuring a consistent supply of fresh, nutritious, food to consumers.

CEA IN HIGH INCOME COUNTRIES: A CASE STUDY OF THE UNITED STATES

Drivers of change

While the US is a net exporter of most agricultural goods, it continues to be a net importer of fruits and vegetables (Curran, 2023) The USDA estimates that as much as 29.5 million metric tons of produce was imported in 2022, an increase of 124% since 2000 (USDA, 2022). As Americans become more aware of where the foods in their diets come from, the demand for locally grown produce will continue to rise. Local cultivation can position the U.S. to become less reliant on imports, especially during the winter months. Additionally, "so-called 'locavorism' has also caught the attention of the nation's largest supermarket chains, nearly all of which have begun to increase their local food procurement" including retailers like Wal-Mart, Costco, and Kroger (Broad, 2020).

Because of consumers' preferences for locally grown produce, land availability can become a concern. Since 2020, land for farming in the U.S. has decreased by 1,300,000 acres as land becomes increasingly scare, especially close to or in urban areas (USDA, 2021). The adoption of CEA can allow for high-density production in a limited space. This makes it possible to grow food where traditional agriculture would be impossible. A subset of CEA facilities in both America and India can be found in table 3. This table denotes different facility types, crops grown, and energy needs of various operations.

Table 3. Case studies of CEA in high and low-to-middle income countries

	Country	**Facility**	**Growth medium**	**Technique**	**Vertical/ single layer**	**Lighting**	**Crops grown**
Bowery Farming Inc.	U.S.A.	Plant factory	Hydroponic	NFT	Vertical	Electricity	Leafy greens
Plenty	U.S.A.	Plant factory	Hydroponic	NFT	Vertical	Electricity	Leafy greens
Oko Farms	U.S.A.	Outdoor	Aquaponic	DWC; grow bags; soil	Single layer	Natural	Leafy greens; herbs; berries; alliums; vine crops
Oishii	U.S.A.	Purpose built	Hydroponic	NFT	Vertical	Electricity	Strawberry
Gotham Greens	U.S.A.	Greenhouse	Hydroponic	NFT	Single layer	Supplemental	Leafy greens; herbs
App Harvest	U.S.A.	Purpose built	Hydroponic	Rockwool slab and highwire; DWC; NFT	Single layer	Supplemental	Tomato; cucumber; leafy greens; strawberry
Aerofarms	U.S.A.	Purpose built	Hydroponic	NFT	Vertical	Electricity	Leafy greens
Intergrow	U.S.A.	Purpose built	Hydroponic	Rockwool slab; highwire	Single layer	Supplemental	Tomato
Upward Farms	U.S.A.	Purpose built	Aquaponic	NFT	Single layer/ vertical	Electricity	Leafy greens; microgreens; fish
eekifood	India	Greenhouse/ polytunnel	Hydroponic	NFT; highwire	Single layer	Natural	Tomato

NutriFresh	India	Greenhouse/ polytunnel	Hydroponic	NFT	Single layer /vertical	Natural	Leafy greens; herbs
Triton Foodworks	India	Greenhouse/ polytunnel	Hydroponic	DWC; NFT	Single layer /vertical	Natural	leafy greens; herbs; tomatoes; cucumbers; strawberries;
Fevin Farms	India	Rooftop polytunnel	Hydroponic	NFT	Single layer	Natural	Leafy greens
Super Greens	India	Purpose built	Hydroponic	NFT	Vertical	Electricity	Leafy greens; herbs
Urban Kissan	India	Purpose built	Hydroponic	NFT	Single layer /vertical	Natural	Leafy greens; herbs
Madhavi Farms	India	Greenhouse/ polytunnel	Aquaponic	DWC	Single layer /vertical	Natural	Leafy greens; herbs

Barriers

Despite the drivers of change for CEA in the U.S., several barriers still hinder more widespread adoption. They include:

1. Capital investment – The initial investment required to set up a CEA facility can be substantial, depending on the type of facility and crop to produce. Additionally, ongoing operational costs can be high, leading to issues with profitability. This is especially true when considering energy costs for heating, cooling, and lighting.
2. Regulatory challenges – Like all industries, regulations play a major role in the formation and operation of safe food production. Depending on the location, farmers might need to

navigate a variety of zoning laws and permits and other regulations which can be time-consuming and costly.

3. Market reach – While the demand for locally grown produce continues to grow, competition with traditional, field grown, products remain high. The cost to produce CEA products can be higher than field grown, yet it can be difficult to command a higher price than what is currently offered.
4. Limited crop selection – Even though there is research into a larger variety of crops, CEA growers still favor quick growing, easy to maintain crops. As table 3 suggests, most crops still grown, whether in poly-hoop tunnels or in plant factories, are leafy greens.

While these barriers can be significant, they can be overcome with the right support. In recent years, many U.S. colleges have also expanded their CEA teaching programs. Also, there are already financial assistance programs and start-ups that help small businesses adopt CEA technologies. Goodman et al. (2019) sums up how legislation is supporting urban agriculture in their case study of CEA in New York City:

> Elected officials have passed legislation to stimulate the use of public land and buildings for UA production generally, though not CEA specifically. These policy initiatives include Local Law 48, which helps the public find City-owned and leased (COLP) space to farm; Local Law 50, which encourages City agencies to purchase produce from New York State vendors; and the Zone Green Text Amendment, which relaxes zoning to allow for higher FAR for rooftop greenhouses.

These laws are helping to expand city agriculture, especially in one of the most populous cities in the world. Addressing the barriers to adoption could increase the reach of CEA in cities, but more research is needed on how this reach will improve food security in high income countries.

CEA IN LOW TO MIDDLE INCOME (LMIC) COUNTRIES: A CASE STUDY OF INDIA

Drivers of change

The Commission on Sustainable Agriculture Intensification (CoSAI) reported that motivations of adopting CEA in LMIC included:

> attracting young people to farming with clean green non-laborious jobs; reducing food loss in transport by producing food closer to markets; enabling farming in and around cities, where land is expensive and may be contaminated or unproductive; protecting crops against extreme weather; enabling continuing cultivation in areas that have become unsuitable for farming due to climate change; increasing domestic production as part of efforts to decrease food import bills; and enabling women and other disadvantaged groups to grow food and access economic and social opportunities (Halliday, 2021).to

Each of these motivations can be seen as reasons why CEA would fill a much-needed niche in the drive for sustainable farming. While some of these motivations are universal, such as enabling farming in and around cities, others are unique to a country like India. These motivations include rising entrepreneurship, climate change and conservation of natural resources, and the need for increased food security.

Due to the warm climate of India, and other countries in the region, low technology poly tunnels and greenhouses are favored over plant factories that are more often found in high income countries, such as the U.S. (or in extreme cold or hot climates). Per AQUASTAT (2022), India has a typical monsoon climate with average annual rainfall of 1,170 mm, mainly occurring between May and September. Temperature ranges from maximums of 42.5°C (108.5°F) in the summer to 29.5°C (81.5°F) in the winter. Because of India’s climate, there is limited need to heat or light a greenhouse. Low to mid tech greenhouses and poly tunnels would be favored over high-tech vertical farms to reduce input costs. CEA would also improve resource efficiency in LMIC where there is still variable energy availability and a heavy reliance on non-renewable energy sources. In India, “over 80% of India’s energy needs are met by three fuels: coal, oil and solid biomass,” making India the third largest emitter of carbon dioxide in the world (India Energy Outlook, 2021). Due to urbanization, there is also competition between agricultural and municipal energy consumption. The addition of low-tech CEA close to cities would provide high-quality food without increased energy competition.

CEA can produce high quality food year-round, thus creating a stable food supply. This stability can improve the other three pillars of food security as well. Predictable crop cycles reduce price fluctuations, thus increasing access and availability. Decoupling food production from the external environment reduces harmful chemical use, making food safer to eat, thus improving its quality, and ultimately its utilization. It also reduces crop losses from farm to consumer.

Barriers

Controlled environment agriculture is not without its limitations. While there has been global investment into CEA, sometimes referred to as novel farming systems, implementation can be hindered by steep investment costs and lack of financial support by the Indian government. Controlled environment agriculture at its core is an agribusiness. In 2021, $2.3 billion was invested into novel farming systems (Agfunder, 2022). Investments for these systems have steadily increased in India from $1.4 million in 2020 to over $15 million in 2022 (Agfunder, 2022). While these numbers are small compared to overall investment into agribusiness, this indicates an appetite for food grown in an innovative and sustainable way. Interestingly, while there are several studies and information speaking to investment into CEA in India, there were no studies that could be found on life cycle costing of CEA production in the same area. Due to the heterogeneous nature of life cycle costing in the literature, a life cycle cost analysis was not performed here. LMIC's, such as India, may experience the same barriers to adoption as HIC's. While education in a place like the U.S. has been expanding, education in other countries for this technology is not always readily available.

However, there are many companies in India that aim to address these issues. For instance, Rise Hydroponics is an agritech company based out of Ahmedabad, Gujarat that promotes hydroponic based farming and helps aspiring CEA producers build out their facilities. Since their start in 2020, they say they have completed 40+ facilities of varying size and systems in 27 cities in India. Kheyti, another agritech company, is supplying Indian smallholders with their "greenhouse-in-a-box" solution. They install greenhouses at 50% lower cost than a traditional greenhouse and provide training and end to end support to their farmers. What both companies have done is increase farmer income and knowledge without increasing detrimental pressures on the environment or incomes of the people they serve. A secondary barrier is the available supply chain and cold storage to prevent food spoilage. By implementing CEA systems closer to cities, the supply chain from farm to consumer is reduced, presumably decreasing food waste.

Facility location and sources of energy are other issues that impacts the sustainability of CEA operations in India. Coal and petroleum made up 44% and 24% of India's total energy consumption in 2020, respectively (India Energy Outlook, 2021). Without advancements in solar, hydropower, or even nuclear energy, CEA could stagnate due to increasing costs. Also, while there are several notable CEA operations in India, including those mentioned in table 3, many are concentrated in major cities such as Mumbai and Pune. This helps to provide fresh produce to municipal centers but is failing the majority of the rural populations.

LIFE CYCLE SUSTAINABILITY ASSESSMENT OF CEA

To further evaluate the sustainability of CEA, a life cycle assessment (LCA) was conducted within the context of developed and developing countries. The goal of this section was to evaluate the environmental and social impacts of controlled environment agriculture (CEA) in a northern climate, such as the United States, versus an equatorial climate such as in India to assess whether CEA is a viable method of sustainable intensification in different climatic conditions.

For all components of this section, the data was aimed at producers of vegetable crops, specifically tomatoes, but could also be used by consumers to assess the impact of their shopping choices. The producers' perspective is important to understand the viability of CEA because, just like traditional farmers, they have the largest financial burden invested with the only revenue typically coming from the marketable yield of the crop. However, there are some limitations to this section. First, formal methods for the any component of the LCSA were not used. Second, this analysis is not being submitted for peer review. Lastly, this study will have some information that can translate to other crops, but it will focus on tomato production so the inputs, outputs, and impacts will not apply to all crops or other production methods. Due to these limitations, the results of the analysis should not be compared to any other studies or be used to directly inform decision-making. Rather, the analysis can serve as a jumping-off point for future, more rigorous analyses. Tomato production grown in a standard greenhouse in a northern temperate region, such as the United States, was compared against CEA in a sub-tropical region, such as India. Tomatoes were chosen because they are the most consumed vegetable worldwide after potatoes (20.8 kg/capita in 2017) (FAO, 2023) and they are commonly grown using CEA methods.

The scope of this LCA includes:

- **System under consideration**: Growing tomatoes in a protected environment in two distinct climates, a temperate region with colder climate versus a sub-tropical/arid region with warmer climate.
- **System's function**: Each system's function is to sustainably produce the highest yield of tomatoes.
- **System's boundaries**: A farmgate boundary for the analysis of the production process only, with no post-farm processing or transportation.
- **Functional unit***:* For greenhouse tomato production, the most common functional unit is in kg/m^2/yr. Most growers and distributors buy and sell based on weight, instead of number of products. The main assumption for this functional unit is that the yield stays steady. Some conversions in downstream analysis will need to be done as some CEA facilities may use tons/acre. It is important to note that these calculations are based off the "fresh" weight produced which is how it is sold to consumers (and tomatoes are comprised of about 80% water).

Environmental Life Cycle

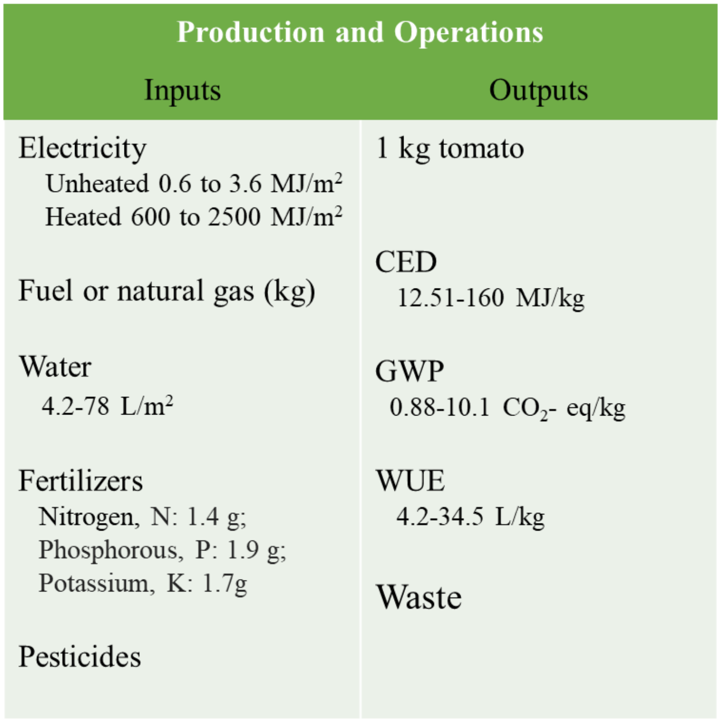
Phase 2: Life cycle inventory

Reduced water use with increased production yields in CEA systems have often been the main arguments for the inclusion of CEA to sustainable agriculture. However, the global warming potential and cumulative energy demands these systems have on the environment also need to be considered. This assessment focused on three impact categories including: the cumulative energy demand (CED), global warming potential (GWP), and water use efficiency (WUE). Several previous studies have used LCA methods to assess the environmental impact of CEA, with varying results based on the system boundaries used and the impact categories chosen. While there were no studies of this kind conducted in India, there were many studies to draw conclusions from comparable sub-tropical and semi-arid environments. These include studies assessing CEA viability in Saudi Arabia and the Mediterranean. Germany and the U.S. were chosen for northern, cold climates. Table 4 lists the life cycle inventory data for production of 1 kg of fresh tomatoes. Unless specified otherwise, all data was secondary, retrieved from primary literature.

Table 4. Life cycle inventory of CEA production

	Reference	**Country**	**Type**	**Functional Unit (FU)**	**Yield (kg/m^2)**	**WUE (liters/kg)**	**GWP (CO_2-eq/kg)**	**CED (MJ/ kg)**
Heated	Ntinas et al. (2017)	Greece	Plastic	1 kg	11.6	34.5	10.1	160.5
	Ntinas et al. (2017)	Germany	Plastic	1 kg	29.4	28.1	0.7	46.1
	Maureira et al. (2022)	USA	Glass	1 kg	71.4	31.6	0.88	12.51
Unheated	Tsafaras et al. (2022)	Saudi Arabia	Glass	1 kg	60	4.2	-	28.8

Figure 3. Life Cycle inventory of CEA production.



Production and Operations	
Inputs	Outputs
Electricity Unheated 0.6 to 3.6 MJ/m^2 Heated 600 to 2500 MJ/m^2 Fuel or natural gas (kg) Water 4.2-78 L/m^2 Fertilizers Nitrogen, N: 1.4 g; Phosphorous, P: 1.9 g; Potassium, K: 1.7g Pesticides	1 kg tomato CED 12.51-160 MJ/kg GWP 0.88-10.1 CO_2- eq/kg WUE 4.2-34.5 L/kg Waste

Phase 3: Life Cycle Impact Assessment (LCIA)

The total yields for the system in all locations were highly variable, possibly due to the level of greenhouse technology, and the duration of growing. Ntinas et al. (2017) saw a yield of only 11.6 kg of tomatoes in a plastic setup over 24 weeks, while Tsafaras et al. (2022) saw 60 kg over 50 weeks. Nederhoff & Stanghellini (2010) note that typical yields of greenhouse tomatoes in high technology greenhouses should range around 50-80 kg/m^2/year. Comparisons in this study were made for similar heated and unheated glass greenhouses that used natural lighting. Energy needs for supplemental light or sole source artificially lit plant factories would be higher but were not compared here.

There was an abundance of literature on polytunnel houses, vertical farms, and on various crops, making true comparisons difficult. Additionally, machinery maintenance was not included in this LCA because of lack of data. In all, the conclusions for the environmental impacts of CEA vary widely depending on the production system, the distance from the consumer, the use or absence of heating energy, or even the packaging of the final product. The only consensus was that CEA grown tomatoes have increased use of energy, decreased use of water, and may have a smaller environmental footprint because of the higher yields they can produce per surface area compared to field grown tomatoes. The GWP may differ widely due to the source of energy used to control the environmental parameters in the greenhouse, such as using hydropower versus fossil fuels. Three impact categories were chosen to make comparisons, as discussed below.

Cumulative Energy Demand (CED)

CED is an indicator for the embodied primary energy in a product or service, as it is calculated as the sum of primary energy that must be spent for the production phase, use phase and disposal

(Nicholson et al., 2020). As many environmental effects are related to CED, it can be a useful tool to estimate the environmental impact of a product or service. The CED was highly variable, ranging from 12.5 to 160 MJ/kg. This is in line with Pineda et al., (2021) who observed that the largest values corresponded to utilization of natural gas and/or oil as the fuel for heating purposes. In unheated greenhouses they found CED ranges from 2.55 to 13.9 MJ/kg, much lower than 28.8 MJ/kg reported by Tsafaras et al, (2021).

Global Warming Potential (GWP)

The GWP is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period, relative to the emissions of 1 ton of carbon dioxide (CO_2). In CEA, it is highly dependent on the choice of energy used, the structure, and the crop. In this study, the GWP was taken directly from primary literature. Even though the greenhouse examples chosen were similar in crop, type, method of production (greenhouse and rockwool slabs), like CED, the GWP was highly variable, ranging from 0.88 to 10.1 CO_2-eq/kg (Maureira et al., 2022; Ntinas et al., 2017; Tsafaras et al., 2022)

Water Use Efficiency (WUE)

WUE is the amount of carbon assimilated as biomass or grain produced per unit of water used by the crop in the production in kilograms, divided by the liters of water used for growing, and is expressed in kg/liter. It is similar to product water use which is the volume of water necessary during the entire production period to produce one kilogram of fresh product, expressed in liters/kg. Across all the literature, these metrics were significantly improved in a greenhouse setting. For example, in their comparison, Nederhoff & Stanghellini (2010) found that tomatoes grown in an unheated greenhouse used an average of 30 liters of water per kilogram produced compared to 60 liters needed for open field cultivation with drip irrigation. The differences were even larger when comparing open field without drip irrigation to an advanced hydroponic setup. Open fields used an average of 100-300 liters while the advanced system used only 15 liters per kilogram.

Phase 4: Interpretation

Energy demand was identified as the main hotspot for CEA production in both cold and sub-tropical climates. The choice of facility and location directly influenced the energy demands. In colder climates, heating accounted for the highest energy demand while in hot and dry climates, evaporative cooling and ventilation was needed. Due to temperature requirements of the plants during vegetative and generative growth, it is common for colder areas to use more energy to heat the greenhouse during the winter. Water use varied based on the method of crop production and choice to recapture water lost by the plant. Crops transpire a lot more water in hot climates than crops in moderate climates. For example, tomatoes transpire 200-900 liters of water per kilogram produced in a hot climate versus 8-150 liters in a cool climate (Nederhoff & Stanghellini, 2010). A closed greenhouse that captures and reuses water from plant transpiration requires more energy but reduces the product water usage per functional unit (Tsafaras et al., 2022).

One externality that could influence the environmental sustainability of greenhouse production is the source of energy.

Environmental sustainability of CEA systems depends largely on the availability of low or zero-carbon energy. (Cowan et al., 2022). However, coal and petroleum are the main sources of energy in India (India EIA, 2021). Even though coal makes up only 10.5% of total energy consumption in the U.S., petroleum and natural gas still makes up 35.1% and 31.3%, respectively

(EIA, 2022). From an environmental standpoint, the location - whether in a hot or a cold climate - of a CEA facility are largely dependent on the energy consumption associated with providing lighting, heating, ventilation, and cooling to the production space (Eaton et al., 2023; Nicholson et al., 2020). Determining the best fit requires information on the source of energy to be used, the timeline of growth, the type of greenhouse to be used, and determinations on what environmental controls that energy will be used for.

There are limitations to this study. To start, complete data for all impact categories was difficult to obtain, due to the complexity of the system boundaries. Additionally, some data like machine maintenance was not available. The data in this study is not based on estimates, but data pulled from primary literature so the variability made it difficult to come to conclusions. Transportation of inputs was also excluded due to the high variability of their sourcing and distance traveled. While there are multiple processes, such as machine maintenance and post-harvest processing, that go into hydroponic tomato production, these are typically wrapped up within the "production" stage. All inputs and outputs go through this stage and much of the literature reviewed did not separate out the distinct processes for their analysis.

Social Life Cycle Assessment

Phase 2: Life cycle inventory

Controlled environment agriculture is advertised as a sustainable solution to agriculture by advancing the goals of the "good food movement" to support local economies, healthy nutrition, fair labor practices, and environmental sustainability (Broad, 2020). The impact categories chosen for this portion of the life cycle assessment included human rights, working conditions, and health and safety, further subdivided into seven subcategories. The stakeholder categories considered were workers, local communities, and society. The stakeholder categories related to consumers and value chain actors were excluded from the scope of the study because they were not relevant within the system boundaries. All the data, aside from the subcategory of fair salary, came from peer reviewed literature. Most of the data described in the literature was qualitative with surveys of specific producers as the main source of information. This could be that there is currently no consistent measurement to reflect the potential social impact of CEA, which is a huge limitation to study robustness.

Phase 3: Impact Assessment

The status for workers of CEA is mixed. Silalahi et al., (2014) noted that greenhouse production offers more permanent work for its employees, but the tradeoff is those employees are subject to long working hours, similar to conventional agriculture. Despite the long working hours, when added into the context of local employment, the status is positively impacted. Young people are more attracted to “agribusiness” jobs than “agriculture” ones (Halliday et al., 2021) and technological advancements are allowing increased employment opportunities in the industry (Wilkinson et al., 2021). Additionally, because the location of these facilities is typically in urban or peri-urban areas, they require help from the communities they serve thus creating jobs for the local economy.

Table *5*. Social life cycle impact assessment

Stakeholder category	**Impact Subcategory**	**Status**	**Evidence**	**Source**
Workers	Fair salary	+	+ At least minimum wage paid to lowest level worker. US - median wage $17/hr. India - median wage $92INR ($1.19 USD equivalent)/hr.	Glassdoor, 2023 Indeed, ND
	Working hours	Mixed	+ Creation of more permanent, year-round, positions.	Silalahi et al., 2014
			- Long working hours.	

Workers	Health and safety	Mixed	-	Workers could have increased exposure to harmful chemicals from fertilizers and pesticides.	Silalahi et al., 2014
			-	Greenhouse workers work throughout one year maintaining the plants, experiencing changes in environmental conditions because of the changing season. Changes in solar radiation and air temperature, such as hot and humid conditions could negatively affect worker's body temperature.	
			+	Workload level of tomato production greenhouse job is considered low, as the job relatively does not require heavy physical work.	
Local Community	Local employment	+	+	Attract young people to farming with clean green non-laborious jobs.	Halliday et al., 2021 Wilkinson et al., 2021
			+	While CEA operations vary in complexity and the use of technology, automation is making the systems more user-friendly. These technological advancements allow for community development through increased employment opportunities and business ventures, even for those with limited or no horticultural experience.	
	Community engagement	Mixed	-	Significant gaps in public understanding of CEA remain.	Broad, 2020 Specht et al., 2014
			+	Increased consumer interest in "good food," that which is not only affordable, nutritious, and tasty, but also promotes values of sustainability and local economic development.	
			+	Facilities can be experienced as teaching spaces, contribute to environmental education, and provide opportunities for practical learning.	
Society	Public commitments to sustainability issues	+	+	Quantity and the diversity of vegetables in the diet were improved. In several cities of developing countries, urban horticulture significantly contributes to food and nutrition security of urban dwellers.	Orsini et al., 2013

Society	Contribution to economic development	Mixed	+ Urban agriculture could be a mechanism for political and social change to reduce disparities, provided that all farmers and gardeners were able to have a say in policymaking. - Commercial viability of CEA depends on the production of high-value products, such as micro greens or tomatoes, which can be sold at a premium, especially in the off-season, making them less accessible to most people.	Specht et al., 2014

Phase 4: Interpretation

Three stakeholder categories were chosen because they offer a more holistic perspective of the social sustainability of CEA than any one category could do. When looking at all three stakeholders, the data suggests that social implications of CEA are neutral to positive. The data collected for each subcategory was not location dependent so no difference between a high income and a low to middle income country could be determined. Most of the data described in the literature was qualitative with surveys of specific producers as the main source of information. This could be that there is currently no consistent measurement to reflect the potential social impact of CEA, which is a huge limitation to study robustness. Ultimately, the social sustainability of any CEA facility will come down to the values of the company. CEA production impacts its workers the most. Even though urban greenhouses have seen growth, many of these facilities are still in semi-rural areas so the local community must be considered in the same context as CEA workers.

From a three-pillars perspective, one location of a controlled environment agriculture facility is not more sustainable than the other. This is due to the number of tradeoffs that location plays in the system itself. These tradeoffs include the choice of the crop and production system, cost of the new venture, and the source of energy to run the operation. The largest tradeoff suggests that to reduce the environmental burden of CEA, the cost of the system will increase, regardless of location.

RECOMMENDATIONS AND CONCLUSIONS

So far, CEA production has been limited to quick growing crops, like lettuce and tomatoes. There is a need for developing systems that expand the range of products grown, including high calorie and high protein crops such as sweet potatoes and green peas. By doing so, CEA can make a bigger impact on reducing hunger in urban areas. Product expansion would also give greater choice to the consumer for healthy, locally cultivated produce. However, CEA cannot be seen as a one size fits all solution for all areas of the world. While innovation is key to sustainable intensification, not all innovations will support food security and accessibility. Especially in HIC's, CEA produced products target the high-end retail markets, making accessibility limited. Affordability will also remain a contentious issue until more efficient and lower cost energy can be used. More research is needed to address the connection of CEA to food security to meet the UN's sustainable development goals.

Aside from product expansion, there is also a need for more economic studies or company benchmarked data to make more direct comparisons between the various systems. Because controlled environment agriculture is often discussed as a more sustainable alternative to traditional agriculture, many life cycle analyses have focused on environmental LCA's. Due to high energy demands, this is especially important to understand opportunities and barriers for increased sustainability. However, until more is understood on the true cost of CEA production in its many forms, it will be hard for this technology to compete with traditional agriculture.

Controlled environment agriculture is part of the future of food production for perishable fruits and vegetables. It has been proven to increase yields of current crops, like lettuce and tomato, while reducing water use. CEA increases employment opportunities, especially to younger generations interested in agribusinesses. While it will not fully replace traditional agriculture, there is a real need for this type of system close to cities.

REFERENCES

2021 AgFunder AgriFoodTech Investment Report. *AgFunder.* (2021). https://agfunder.com/research/2021-AgFunder-agrifoodtech-investment-report/

Agriculture in India: Information About Indian Agriculture & Its Importance. *India Brand Equity Foundation*. (2022). https://www.ibef.org/industry/agriculture-india

AQUASTAT FAO's Information System on Water and Agriculture. Rome. *FAO*. [Software, E-Resource] https://data.apps.fao.org/aquamaps/

Armanda, D. T., Guinée, J. B., & Tukker, A. (2019). The second green revolution: Innovative urban agriculture's contribution to food security and sustainability – A review. *Global Food Security*, *22*, 13–24. https://doi.org/10.1016/j.gfs.2019.08.002

Broad, G. M. (2020). Know Your Indoor Farmer: Square Roots, Techno-Local Food, and Transparency as Publicity. *American Behavioral Scientist*, *64*(11), 1588–1606. https://doi.org/10.1177/0002764220945349

Cowan, N., Ferrier, L., Spears, B., Drewer, J., Reay, D., & Skiba, U. (2022). CEA Systems: The Means to Achieve Future Food Security and Environmental Sustainability? *Frontiers in Sustainable Food Systems*, *6*. https://www.frontiersin.org/articles/10.3389/fsufs.2022.891256

Curran, J. (2023, March). *Hydroponic Crop Farming in the US*. https://my.ibisworld.com/us/en/industry-specialized/od4012/industry-at-a-glance

DataM Intelligence, https://www.datamintelligence.com/. (2022, November 7). India hydroponics market size share growth opportunities and forecast 2022. *DataMIntelligence.* https://www.datamintelligence.com/research-report/india-hydroponics-market

Eaton, M., Shelford, T., Cole, M., & Mattson, N. (2023). Modeling resource consumption and carbon emissions associated with lettuce production in plant factories. *Journal of Cleaner Production*, *384*, 135569. https://doi.org/10.1016/j.jclepro.2022.135569

Engler, N., & Krarti, M. (2021). Review of energy efficiency in controlled environment agriculture. *Renewable and Sustainable Energy Reviews*, *141*, 110786. https://doi.org/10.1016/j.rser.2021.110786

FAO (2011). The state of the world's land and water resources for food and agriculture (SOLAW) – Managing systems at risk. *Food and Agriculture Organization of the United Nations*, Rome and Earthscan, London.

FAO. 2015. AQUASTAT Country Profile – India. *Food and Agriculture Organization of the United Nations (FAO)*. Rome, Italy https://www.fao.org/3/ca0394en/CA0394EN.pdf

FAO. (2017). The Future of Food and agriculture: Trends and challenges. *Food and Agriculture Organization of the United States*. ISBN 978-92-5-109551-5

Fao in India. India at a glance | FAO in India | *Food and Agriculture Organization of the United Nations*. (2022). https://www.fao.org/india/fao-in-india/india-at-a-glance/en/

Goodman, W., & Minner, J. (2019). Will the urban agricultural revolution be vertical and soilless? A case study of Controlled Environment Agriculture in New York City. *Land Use Policy*, *83*, 160–173. https://doi.org/10.1016/j.landusepol.2018.12.038

Gómez, C., Currey, C. J., Dickson, R. W., Kim, H.-J., Hernández, R., Sabeh, N. C., Raudales, R. E., Brumfield, R. G., Laury-Shaw, A., Wilke, A. K., Lopez, R. G., & Burnett, S. E. (2019). Controlled Environment Food Production for Urban Agriculture. *HortScience*, *54*(9), 1448–1458. https://doi.org/10.21273/HORTSCI14073-19

Grower salary in India. (n.d.). Indeed. https://in.indeed.com/career/grower/salaries

Halliday, J., Kaufmann, R. von, & Herath, K.V. (2021). An assessment of controlled environment agriculture (CEA) in low- and lower-middle income countries in Asia and Africa, and its potential contribution to sustainable development. Colombo, Sri Lanka: Commission on Sustainable Agriculture Intensification. CGIAR Research Program on Water, Land and Ecosystems (WLE). 86p.

Hinz, R., Sulser, T. B., Huefner, R., Mason-D'Croz, D., Dunston, S., Nautiyal, S., et al. (2020). Agricultural development and land use change in India: A scenario analysis of trade-offs between UN Sustainable Development Goals (SDGs). *Earth's Future*, 8, e2019EF001287. https://doi.org/10.1029/2019EF001287

India EIA (2021), India Energy Outlook 2021, IEA, Paris https://www.iea.org/reports/india-energy-outlook-2021

India 2021 Agrifood Startup Investment Report. *AgFunder*. (2022). https://agfunder.com/research/india-2021-agrifood-startup-investment-report/

IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press.

Lefers, R. M., Tester, M., & Lauersen, K. J. (2020). Emerging technologies to enable sustainable controlled environment agriculture in the extreme environments of Middle East-North Africa coastal regions. *Frontiers in Plant Science, 11*. https://doi.org/10.3389/fpls.2020.00801

Li, M., Jia, N., Lenzen, M., Malik, A., Wei, L., Jin, Y., & Raubenheimer, D. (2022). Global food-miles account for nearly 20% of total food-systems emissions. *Nature Food*, *3*(6), Article 6. https://doi.org/10.1038/s43016-022-00531-w

Maureira, F., Rajagopalan, K., & Stöckle, C. O. (2022). Evaluating tomato production in open-field and high-tech greenhouse systems. *Journal of Cleaner Production*, 337, 130459. https://doi.org/10.1016/j.jclepro.2022.130459

Medina, A., Cooman, A., Parrado, C. A., & Schrevens, E. (2006). *Evaluation of energy use and some environmental impacts for greenhouse tomato production in the high-altitude tropics* (Vol. 718). International Society for Horticultural Science. https://doi-org.proxy.library.cornell.edu/10.17660/actahortic.2006.718.48

NASA. (2023, February 7). *Overview: Weather, Global Warming and climate change*. NASA. https://climate.nasa.gov/global-warming-vs-climate-change/

Naseer, M., Persson, T., Hjelkrem, A.-G. R., Ruoff, P., & Verheul, M. J. (2022). Life cycle assessment of tomato production for different production strategies in Norway. *Journal of Cleaner Production*, *372*, 133659. https://doi.org/10.1016/j.jclepro.2022.133659

Nederhoff, E., & Stanghellini, C. (2010). Water use efficiency of tomatoes - in greenhouses and hydroponics. Practical Hydroponics & Greenhouses *2010*. 115.

Nicholson, C. F., Harbick, K., Gómez, M. I., & Mattson, N. S. (2020). An Economic and Environmental Comparison of Conventional and Controlled Environment Agriculture (CEA) Supply Chains for Leaf Lettuce to US Cities. Food Supply Chains in Cities (pp. 33–68). *Springer International Publishing*. https://doi.org/10.1007/978-3-030-34065-0_2

Ntinas, G. K., Neumair, M., Tsadilas, C. D., & Meyer, J. (2017). Carbon footprint and cumulative energy demand of greenhouse and open-field tomato cultivation systems under Southern and Central European climatic conditions. *Journal of Cleaner Production*, *142*, 3617–3626. https://doi.org/10.1016/j.jclepro.2016.10.106

Orsini, F., Kahane, R., Nono-Womdim, R., & Gianquinto, G. (2013). Urban agriculture in the developing world: A review. *Agronomy for Sustainable Development*, *33*(4), 695–720. https://doi.org/10.1007/s13593-013-0143-z

Paucek, Ivan & Appolloni, Elisa & Pennisi, Giuseppina & Quaini, Stefania & Gianquinto, Giorgio & Orsini, Francesco. (2020). LED Lighting Systems for Horticulture: Business Growth and Global Distribution. *Sustainability*. 12. 7516. 10.3390/su12187516.

Peña, A., Rovira-Val, M. R., & Mendoza, J. M. F. (2022). Life cycle cost analysis of tomato production in innovative urban agriculture systems. *Journal of Cleaner Production*, 367, 133037. https://doi.org/10.1016/j.jclepro.2022.133037

Pineda, I. T., Lee, Y. D., Kim, Y. S., Lee, S. M., & Park, K. S. (2020). Review of inventory data in life cycle assessment applied in production of fresh tomato in greenhouse. *Journal of Cleaner Production*, 282, 124395. https://doi.org/10.1016/j.jclepro.2020.124395

Pingali, P. L. (2012). Green Revolution: Impacts, limits, and the path ahead. *Proceedings of the National Academy of Sciences*, *109*(31), 12302–12308. https://doi.org/10.1073/pnas.0912953109

Salary: Greenhouse Worker (April 2023). (n.d.). Glassdoor. https://www.glassdoor.com/Salaries/false

Serrano-Carreón, L., Aranda-Ocampo, S., Balderas-Ruíz, K. A., Juárez, A. M., Leyva, E., Trujillo-Roldán, M. A., Valdez-Cruz, N. A., & Galindo, E. (2022). A case study of a profitable mid-tech greenhouse for the sustainable production of tomato, using a biofertilizer and a biofungicide. Electronic Journal of Biotechnology, 59, 13–24. https://doi.org/10.1016/j.ejbt.2022.06.003

Silalahi, R., Ushada, M., Falah, M., Takayama, K., Takahashi, N., & Nishina, H. (2014). Assessment of Workers' Body Temperature and Workload in Tomato Production Greenhouse Work. *Agroindustrial Journal*, *3*, 133–139. https://doi.org/10.22146/aij.v3i1.25029

Specht, K., Siebert, R., Hartmann, I., Freisinger, U. B., Sawicka, M., Werner, A., Thomaier, S., Henckel, D., Walk, H., & Dierich, A. (2014). Urban agriculture of the future: An overview of sustainability aspects of food production in and on buildings. *Agriculture and Human Values*, *31*(1), 33–51. https://doi.org/10.1007/s10460-013-9448-4

Specht, K., Siebert, R., & Thomaier, S. (2016). Perception and acceptance of agricultural production in and on urban buildings (ZFarming): A qualitative study from Berlin, Germany. *Agriculture and Human Values*, *33*(4), 753–769. https://doi.org/10.1007/s10460-015-9658-z

Tsafaras, I., Campen, J. B., de Zwart, H. F., Voogt, W., Harbi, A. A., Assaf, K. A., Abdelaziz, M. E., Qaryouti, M., & Stanghellini, C. (2022). Quantifying the trade-off between water and electricity for tomato production in arid environments. *Agricultural Water Management*, *271*, 107819. https://doi.org/10.1016/j.agwat.2022.107819

U.S. Energy Information Administration (EIA), Monthly Energy Review (April 2022), Table 1.3 and 2.1-2.6

U.S. fruit and vegetable import value outpaces volume growth. (13 July 2022). USDA. http://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=104212

What is Food Security? There are Four Dimensions. (2023). *World Bank*. https://www.worldbank.org/en/topic/agriculture/brief/food-security-update/what-is-food-security

Zhou, D., Meinke, H., Wilson, M., Marcelis, L. F. M., & Heuvelink, E. (2021). Towards delivering on the sustainable development goals in greenhouse production systems. *Resources, Conservation and Recycling*, *169*, 105379. https://doi.org/10.1016/j.resconrec.2020.105379