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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

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Hydroponic bell peppers (*photo*: Chaminda Ranasinghe).

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List of abbreviations and acronyms

AI	Artificial intelligence
CEA	Controlled environment agriculture
CoSAI	Commission on Sustainable Agriculture Intensification
DWT	Deep water culture
INMED	INMED Partnerships for Children, formally International Medical Services for Health
IUA	Innovative urban agriculture
NFT	Nutrient film technique
SAI	Sustainable Agriculture Intensification
SDG	Sustainable Development Goals
STEM	Science, technology, engineering and mathematics
WLE	CGIAR Research Program on Water, Land and Ecosystems

Executive summary

Controlled Environment Agriculture (CEA) is the production of plants, fish, insects, or animals inside structures such as greenhouses, vertical farms, and growth chambers, in which environmental parameters such as humidity, light, temperature and CO_2 can be controlled to create optimal growing conditions.

To date, the majority of high-tech CEA installations are concentrated in high-income, industrialized countries, and the term is often associated with fully automated vertical farms in purpose-built buildings or repurposed spaces, such as disused warehouses, underground bomb shelters, office walls and basements, and even barges. Some forms of CEA are, nonetheless, being successfully taken up by entrepreneurs and established farmers in low- and lower-middle income countries, including in Africa and Asia. While the CEA techniques used in these contexts may not be so technologically advances, they show promise for their contribution to sustainable agricultural intensification (SAI).

Present trends of agriculture intensification run counter to the Sustainable Development Agenda (UN, 2015). They seek to meet the food and nutrition needs of a rapidly growing and urbanizing global population by expanding areas under cultivation, and through increased use of chemical fertilizers, weed killers and pesticides that natural resources under tremendous pressure, cause biodiversity loss, degrade water catchments and contribute to greenhouse gas emissions, a major driver of climate change (IPCC, 2019).

SAI, on the other hand, is based on methods that are productive, energy-efficient, less-resource intensive, and robust to the effects of natural hazards, pest and diseases. These methods, and the policies, institutions and financial instruments they require, must be geared towards addressing the poverty and inequality that are associated with intractable food insecurity and malnutrition, particularly in low- and lower-middle income countries.

For CEA to make a meaningful contribution to SAI in low- and lower-middle income countries, there is a need for investment in research, capacity development, enterprise initiation, scaling, and creation of enabling environments (through policies at national and sub-national levels). To attract investment and justify policy change, more information is needed on the potential contribution of CEA to sustainable development, and where, how, by whom, and for whom various technologies might be best deployed.

The purpose of this report is:

- to identify which CEA technologies merit investment, and under which conditions, to advance SAI in Africa and Asia;
- to make recommendations concerning investment in CEA technologies.

To do this, we conducted a study on the current practice and future potential of CEA in low- and lower-middle income country contexts, consisting of a literature review, document analysis, and in-depth interviews with 12 CEA practitioners in four countries: Kenya, Nigeria, India, and Sri Lanka.

The study addressed three questions:

1) Which CEA technologies are most likely to be viable in low- and lower-middle income countries in Asia and Africa, in terms of making use of locally-available human, capital and natural resources and production efficiency?
2) In what ways can CEA contribute to the sustainable development objectives of SAI in low- and lower-middle income contexts?
3) What are the enablers and barriers facing potential CEA practitioners to starting up and running successful CEA enterprises and to the overall advancement of CEA in Asia and Africa?

Study findings

Viable CEA technologies

Our evidence supported the principle that the type, systems and control parameters in CEA must be tailored to local contexts.

Generally, however, greenhouses and polytunnels were seen to be viable in all the study contexts, in particular those with structural features that harnessed local energy and managed heat through ventilations without use of artificial energy. They can be built and equipped cheaply (often with local materials), they can be repaired using manual labor, and capacity can be scaled up with the addition of new units.

Shipping containers and repurposed buildings have the advantages of enabling entrepreneurs to set up close to market, although the reduced fuel costs for transporting produce from the countryside are off-set by higher energy costs. Operators may also trade in post-harvest loss of conventionally grown produce due to poor distribution infrastructure for lost crops due to outages of energy, on which LED and air conditioning systems rely.

Hydroponic systems were found to be viable for vegetable production, even in inhospitable drylands, due to their minimal water use. In most contexts cheap, locally-available materials were available for use as substrates. Gravity-driven nutrient delivery methods such as the Kratky system and Ebb and Flow are most suitable in situations where electricity is expensive and irregular. Growing on vertical, pyramid or A-frame structures were preferable to mono layer beds, because they provide greater growing area while still enabling use of natural sunlight.

Aquaponics is a viable where the higher water and energy needs can be accommodated, and its two outputs – vegetables and fish – provide complementary nutrition sources and income streams. Again, vertical structures are preferable to optimize growing space and sun exposure.

BSF farming is considered viable due to low start-up costs and low energy use. It is unlikely to appeal to the same entrepreneurs as hydroponics and aquaponics, however, because the outputs are animal feed and compost, rather than food for human consumption.

Contribution to sustainable development

Evidence from CEA operators in all study contexts points to significant contributions to aspects of sustainable development.

In food security, the emphasis was on improved food quality and nutritional value, and supporting affordability by reducing price fluctuations throughout year. Greater contributions to food security are expected in the future as costs come down and operators are able to grow traditional produce for the local market, rather than exotic varieties for high-end niches. CEA is also expected to help maintain access and availability of nutritious food in the face of climate hazards, as well as to stem the drift of young people away from farming.

For poverty reduction and social equity, CEA showed particular promise for enabling people to escape poverty through employment, whether by operators directly, through development of an outgrower network, or by prompting supply chain development that leads to more economic opportunities. Entrepreneurship is not seen as a general route out of poverty or for social equity due to exclusive start-up costs and level of education required, but it can lead to more lucrative farm-based livelihood for people with means. Accessibility of CEA to women differs between the study contexts, with interviewees deliberately creating preferential opportunities for women. There was some evidence to support benefits of CEA for displaced people and refugees, with support of international organizations to supply equipment and local experts or NGOs to advise.

In terms of resource use and natural environment: The forms of CEA practiced in the study contexts were generally selected for their viability to climate- and resource-related constraints, particularly with regard to energy and water, rather than to ameliorate challenges. However, CEA was seen as a means to ameliorate land use pressures, and reduced or zero pesticide use, reduced carbon emissions, and waste reduction were three areas of natural environment protection.

CEA techniques and conditions that may merit investment

Based on our findings, we suggest the following techniques and conditions for CEA operations may be worthy of investment, subject to analysis of local context, including climatic conditions, market structure, input availability, and policy context.

- Hydroponics, and aquaponics, and BSF farming practiced in greenhouses and polytunnels, in particular those that can be constructed cheaply using locally-available materials, and with structural features for controlling the growing environment.
- Hydroponics, aquaponics and BSF farming practiced in re-purposed buildings and other spaces in urban areas (including those that make use of readily available materials such as disused shipping containers).
- For hydroponics and aquaponics, nutrient delivery techniques that require as little water movement that is dependent on artificial energy as possible; where there are higher water and energy requirements, there must be significant productivity returns.
- For hydroponics and aquaponics, vertical (multi-layer or A-frame) structures to make better use of limited spaces and maximum use of natural sunlight.
- CEA systems with two outputs that provide dual sources of nutrition and/or income streams.
- Systems that use local materials as inputs, and in particular those that use waste streams from other industries inputs.
- Small- to medium scale operations, which are relatively affordable for smallholder farmers and young entrepreneurs. Scalability of operations is an asset, such as addition of new structures using the same basic infrastructure, or through franchise or outgrower models.
- CEA operations that produce traditional, locally-consumed vegetables that can be sold at a stable price via local markets year round.

- CEA operations close to the place of consumption to avoid loss and degradation of quality through long-distance transportation and to minimize risk of distribution disruptions. This includes urban and peri-urban areas and city regions, where land use pressures, soil, pollution or climatic conditions may make open field agriculture difficult.
- CEA operations in areas where residents have limited access to nutritious food, and where environmental conditions are unsuitable for most food-growing, such as in settlements for displaced people.
- Cooperatives or clusters of CEA operators within a locality, which bring multiple benefits to growers and stimulate economic opportunities by incentivizing the development of supply- and value chains.

Enablers and barriers to CEA

The report concludes that African and Asian countries have the necessary ingredients for growing the CEA subsector into a significant complementary adjunct to open field agriculture, notably in terms of:

- (micro) financial institutions' purported interest in agriculture;
- existing practice of (outdoor) urban agriculture in some contexts (subject to regulations);
- a young workforce that is seeking white-collar jobs that are less dirty and labor intensive than traditional agriculture, and that is willing to learn and apply STEM skills;
- established agricultural universities and agricultural extension departments;
- local resources that can be used in CEA, including by-products of other industries and organic waste.

However, the study uncovered significant barriers, both to the start-up and successful operation of CEA businesses and to the wider take-up of technologies in these contexts. These relate to:

- financial institutions' awareness and knowledge of CEA and suitability of finance options;
- lack of access to land in some settings (and lack of access to land with an electricity supply);
- planning exclusions due to poor understanding of what CEA entails;
- lack of a secure, stable market for produce;
- inherent business risks and lack of secure career prospects;
- lack of specialist, up-to-date training and extension support for CEA techniques;
- where private training is available, perceived propriety and safety for women attendees;
- lack of R&D funding to solve problems encountered;
- lack of access to affordable emerging technologies; lack of supply chains for some essential inputs, in some contexts;
- import regulations for seeds, nutrients, and greenhouse materials in some contexts; and poor separation of waste, which is not viewed as a resource.

Recommendations

The report makes a series of recommendations, assuming that viable models of CEA will be identified and defended by credible investor pitches. This appears to be a relatively safe assumption in view of increasing number of successful CEA enterprises and the certainty that the demand for not only food but for safe, health nutritious food will inevitably continue to increase in Africa and Asia.

The recommendations are directed at a variety of investors, including banks, micro finance institutions and parastatal agricultural finance agencies; national governments; agriculture departments; overseas governments; grant-making bodies and NGOs; private equity investors; private businesses; technology developers; public research institutes.

Recommendation 1: Financing of new CEA businesses that includes living costs for an initial period to avoid entrepreneurs using their loans for everyday expenses, with a payback period that begins only when the activity becomes profitable.

Recommendation 2: Establishment of dedicated CEA agribusiness/arbitrageur programs and incubators under the agricultural development programs of grant-making bodies and NGOs, including ring-fenced initiatives for women, youth, and disadvantaged groups.

Recommendation 3: Incentive schemes for career development to reduce the risk for new entrants, such as the opportunity for the best trainees to win start-up funds, and mid-career awards.

Recommendation 4: Removal of trade barriers such as tariffs on specialist CEA equipment, and simple, accessible processes for benefiting from the changes.

Recommendation 5: Support for supply chain development to ensure CEA practitioners have access to inputs (including seeds that are optimized for CEA, access to waste streams as inputs), and to create additional economic opportunities.

Recommendation 6: Support for post-harvest value chains to ensure CEA practitioners have access to processing, storage and distribution infrastructure, to reduce loss and enable better supply-demand management.

Recommendation 7: Support for the organization of CEA practitioners into associations or cooperatives, to optimize access to investment, and to enable peer-to-peer support, supply chain development, and collective lobbying.

Recommendation 8: Formation of public-private partnerships for CEA clusters or tech-hubs, where growers can work collectively or in close proximity, allowing them to share experiences and information, leverage economies of scale on equipment and inputs, and market collectively.

Recommendation 9: Funding for facilities and equipment for demonstrating CEA installations in schools and universities, and teaching materials on greenhouse growing, including various forms of CEA, to be included in school and university curricula

Recommendation 10: Investment in training and extension services, specific local needs, and is regularly updated to include emerging technologies.

Recommendation 11: Investment in awareness and market development among both farmers and buyers, and support development of a stable marketing channel.

Recommendation 12: Research funding on optimal technologies for reducing energy consumption, reducing costs, development and use of less synthetic nutrient solutions, and more efficient new approaches.

Recommendation 13: Overseas trade and development programs, including exchange visits to encourage and facilitate private companies to invest in new (low- and lower-middle income) markets.

Recommendation 14: R&D technology trials in low- and lower-middle income contexts, to help ensure inventions are optimized for the environments and economic realities of these contexts and to provide access to new developments as early as possible.

In addition, the report makes a several **policy recommendations** aimed at national, regional, and local governments, to establish an enabling environment for the CEA sector to develop.

Policy recommendation 1: Adoption of integrated policies that promote adoption of CEA, including across agricultural development, food security and nutrition, economic development and employment, land use planning policies.

Policy recommendation 2: Development of evidence-based industry standards and regulations, that are conducive, relevant, and appropriate.

Policy recommendation 3: Establishment of regulatory standards on nutrients required in hydroponic growing, as a reference for customs inspections to avoid import bans or inconsistency.

Policy recommendation 4: Design of a process for obtaining permits to practice CEA (where required under regulatory frameworks) that promotes ease of doing business.

Policy recommendation 5: Taking into account CEA in local planning frameworks, including specifications in zoning ordinances and/or urban agriculture regulations, integration into spatial design and building codes, development of supportive infrastructure.

1. Introduction

Towards Sustainable Agriculture Intensification

The world is in the throes of unprecedented population growth and urbanization. By 2050, it is expected that there will be 9.7 billion humans on Earth (up from an estimated 7.7 billion in 2019), 68% of whom will inhabit urban areas (UNDESA, 2018; UNDESA, 2019). Low-income countries of the Global South – in particular Africa and Asia – will see a disproportionate share of this growth, with the emergence of new mega-cities (over 10 million) and large cities (5 to 10 million).

The UN Sustainable Development Agenda (UN, 2015) provides a framework of 17 sustainable development goals (SDGs) for countries to manage this growth while meeting the needs of citizens – now and in the future. However, present trends of agriculture intensification that seek to meet increased food and nutrition needs by expanding areas under cultivation and increased use of chemical fertilizers, weed killers and pesticides place natural resources under tremendous pressure, cause biodiversity loss, degrade water catchments and contribute to greenhouse gas emissions, a major driver of climate change (IPCC, 2019). As such, they run counter to the Sustainable Development Agenda.

For the future of humanity, it is vital that the natural environment should not be further harmed. There is an urgent need for innovative methods of **sustainable agricultural intensification** (SAI) that are productive, energy-efficient, less-resource intensive, and robust to the effects of natural hazards, pest and diseases. These methods, and the policies, institutions and financial instruments they require, must be geared towards addressing the poverty and inequality that are associated with intractable food insecurity and malnutrition, particularly in low- and lower-middle income countries.

Within this context, the Commission on Sustainable Agriculture Intensification (CoSAI) was initiated by the CGIAR Research Program on Water, Land and Ecosystems (WLE) in June 2020 with the aim of generating public and private support for innovation to rapidly scale up SAI in low- and lower-middle income countries.

One promising technological contribution to SAI is Controlled Environment Agriculture (CEA), which is the production of plants, fish, insects, or animals inside structures such as greenhouses, vertical farms, and growth chambers, in which environmental parameters such as humidity, light, temperature and CO_2 can be controlled to create optimal growing conditions (see chapter 2 below for details of various CEA technologies). While CEA is still only making a marginal contribution to SAI, over the last decade interest in it has grown and diversified among entrepreneurs, agronomists, and academics across multiple disciplines – from plant science, to microbiology, public health, sociology, architecture, and more. Architects have embraced CEA in a sub-discipline labelled as ‘agritecture’.

The total market value of vertical farming alone is estimated to have increased from US$ 0.4 bn in 2013 to US$ 2 bn in 2020, with a further hike to US$6.4 bn forecast by 2023 (Hotten, 2019).

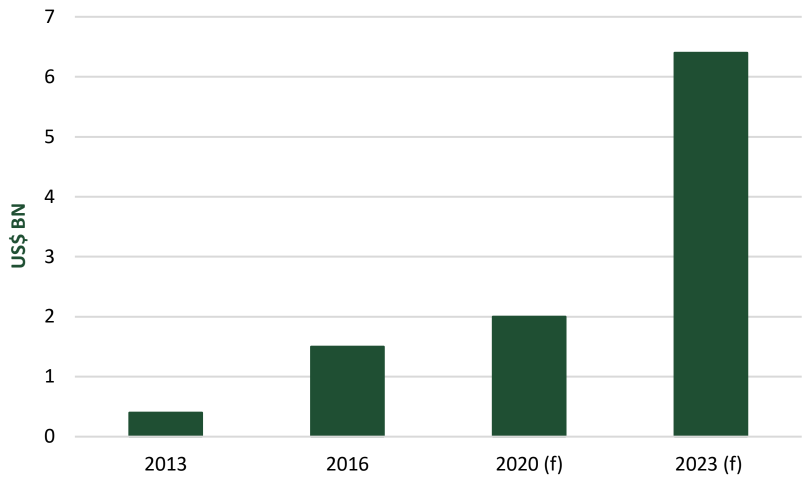

Figure 1: Total market value of vertical farming worldwide (US$ bn)
Source: BBC Research, as cited by Hotten (2019)

To date, the majority of high-tech CEA installations are concentrated in high-income, industrialized countries. The most advanced high-tech approaches may not be adoptable or appropriate in less developed economies, but some forms of CEA are, nonetheless, being successfully taken up in low- and lower-middle income African countries, as documented in a special issue of Agriculture for Development magazine (Kaufmann, 2018a). For these to make a meaningful contribution to SAI in the Global South, however, there is a need for investment in research, capacity development, enterprise initiation, scaling, and creation of enabling environments (through policies at national and sub-national levels). To attract investment and justify policy change, more information is needed on the potential contribution of CEA to sustainable development, and where, how, by whom, and for whom various technologies might be best deployed.

The purpose of this report, therefore, is:

- to identify which CEA technologies merit investment, and under which conditions, to advance SAI in Africa and Asia;
- to make recommendations concerning investment in CEA technologies.

To do this, we conducted a study on the current practice and future potential of CEA in low- and lower-middle income country contexts. The study addressed three questions:

1) Which CEA technologies are most likely to be viable in low- and lower-middle income countries in Asia and Africa, in terms of making use of locally-available human, capital and natural resources and production efficiency?
2) In what ways can CEA contribute to the sustainable development objectives of SAI in low- and lower-middle income contexts?
3) What are the enablers and barriers to the start-up and successful operation of CEA enterprises using these promising technologies, and to the overall advancement of CEA in Asia and Africa?

Report structure

Chapter 2 starts with a search for a working definition of CEA, which comes in many different forms. This is followed by a brief overview of the global trends in CEA and the motives for adopting different options.

Chapter 3 presents the main purpose and outcomes of the study, commencing with the methodology.

The chapter then sets out the findings relating to the most suitable CEA technologies in low- and lower-middle income countries.

The contributions of CEA to development are discussed in global and specifically African and Asian contexts, in relation to food security (including nutritional value, affordability, and access in the context of climate events and the farming workforce), poverty reduction and social equity; and resource use and the natural environment.

The conclusion is drawn from the first two study questions that, with the right technologies, CEA enterprises can be viable and can make some positive contributions to food security and nutrition, poverty reduction and social equity, and resource use and the natural environment. It identifies some CEA technologies and suitable conditions that particularly merit investment to advance SAI in Africa and Asia.

Chapter 3 ends with presentation of the study findings related to enablers and/or barriers to CEA take-up, viability, and widespread adoption in low- and lower-middle income countries. The findings are grouped under ten thematic headings.

Finally, **Chapter 4** sets out specific recommendations related to investment and enabling policies, made with a view to harnessing enablers and overcoming specific barriers to successful entry and operation of CEA businesses.

2. Controlled Environment Agriculture (CEA)

Definition and variations of CEA

For the purposes of this report, controlled environment agriculture (CEA) involves the production of plants, fish, insects, or animals inside structures, in which environmental parameters such as light, temperature and CO_2 can be controlled to create optimal growing conditions[1].

CEA technologies are classified according to a) type of the facility; and b) the growing system(s) used (Agrilyst, 2017).

CEA facilities range from simple, low-tech systems such as poly tunnels (plastic hoop houses), through mid- and high-tech greenhouses (glass or plastic), to completely enclosed, advanced systems such as indoor vertical gardens, container farms, and floating greenhouses, with artificial lighting and fully automated climate and growth controls. CEA systems can be installed in limited spaces such as rooftops, backyards, and shipping containers; in abandoned buildings, basements, and other vacant indoor spaces; or in dedicated, purpose-built structures. A key feature of advanced CEA technologies is the ability to use space in three dimensions; the vertical dimension enables high quantities of food to be produced on small footprints.

The principal CEA technologies are either soil-based, hydroponic, aeroponic, or aquaponic.

- Soil-based CEA systems use regular soil or compost as the plant growth medium.
- In hydroponic systems, solutions containing nutrients are applied directly to the roots of the plants, with water serving as the growing medium or a substrate (Kagan and Riemenschneider, 2018). There are several types of hydroponic system (Maucieri et al., 2019):
  - Deep water culture (DWC): the plant root system is submerged directly in the aerated nutrient solution;
  - Nutrient film technique (NFT): the nutrient solution is plumped down sloped channels over the plant roots, which are contained in net pots;
  - Kratky system: plants are in net cups filled with a growth medium, which are suspended over a reservoir containing the nutrient solution, with only the root tips touching it. No electricity is required, nor additional nutrients after the initial filling of the reservoir.

[1] This definition is not formal or universal but was determined to be broad enough to cover the wide range of low- to high-tech facility types that are appropriate in low and lower-middle income country contexts, through to high-income industrialised countries. The plant growing systems listed are not exclusive. Various practitioners, researchers and institutions use the term in slightly different, more restrictive ways. For instance, the New York State Energy and Research Development Authority definition excludes low-tech greenhouses and tunnel field applications on the ground that the environment is not 100% controlled (NYSERA, 2021); Cornell University uses the term for only 'advanced and intensive hydroponically-based agriculture', to the exclusion of other growing systems (Cornell, 2021). Others prefer other terms for similar (not necessarily identical) concepts. For example, the terms 'vertical farm' and 'plant factory' (Butterini and Marcelis, 2020; Despommier, 2019; Graamans et al., 2018) are sometimes used synonymously with CEA in high-income contexts; Armanda et al. (2019) used the term 'innovative urban agriculture' (IUA) as an umbrella for indoor agriculture, remote sensing, vertical agriculture, hydroponic, aeroponic, and soilless agriculture, precision ag, and other novel technologies, both open and closed.

- Wick system: Plants are in an absorbent substate (e.g. perlite, varulite) with nylon wicks positioned around their roots that draw the nutrient solution up from a reservoir below. No electricity is required.
- Drip system: plant roots are placed in a growing medium (e.g. sand, coir, wood fiber, etc.), and controlled amounts of the nutrient solution are pumped directly to the base of each plant;
- Ebb and flow: plants are placed in a growing medium. A pump with a timer intermittently floods the grow bed with nutrient solution then drains it away.

• In an aeroponic system the plant roots are suspended in air and misted with nutrient-enriched water, either intermittently or continuously. Some scientists consider aeroponics to be a variant of hydroponics because the nutrients are contained in water (Lakhiar et al., 2018).
• Aquaponic is a dual, closed-loop production system comprising aquaculture (fish cultivation) and hydroponics. In the aquaculture tank microbial activity converts fish excreta into nutrients. The nutrient-rich wastewater is then pumped through the hydroponic area for use as the plant nutrient. The plants take up the nutrients and clean the water, which is then cycled back into the fish tank (Thorarinsdottir, 2015).

One of the most extensively practiced CEA technologies is insect farming. On a global scale Black Soldier Fly (*Hermetia illucens L*.) farming is most widespread. Black Soldier Flies (BSF) are benign insects, the larvae of which play an important role in the decomposition of organic matter (such as plant and food waste and feces). The larvae themselves are a cheap, nutrient rich by-product of the process with multiple uses, such as biofertilizer, animal feed, and for oil extraction (Joly and Nikiema, 2019). In BSF farming, the biological processes are engineered to optimize the life cycle of the BSF through the careful control of feedstock (particle size, pH, nutrient content, moisture content, C: N ratio, and the structure) and the growing environment (temperature, humidity and light) (Joly and Nikiema 2019).

CEA technologies are not mutually exclusive and more than one growing system can be maintained within one CEA facility, particularly where CEA systems use each other's waste streams, such as in aquaponics (Agrilyst, 2017) or in the co-location of mushrooms and plants, BSF and fish, or BSF and mushrooms (Styles and Wootton-Beard, 2017; van Acker et al., 2017).

The appropriate type(s) of growing system depends on the type of facility, the amount of space available, the growth medium (often a question of what materials are readily and affordably available locally), and – for low-tech facilities – the local environmental conditions. Not every CEA facility and/or growing system is suitable for every location or situation. The success of CEA enterprises depends on finding the most appropriate combinations of affordable facilities and growing systems in the prevailing market and environmental contexts (Agrilyst, 2017), and the plant varieties and environments must be constantly matched to produce optimum yields (Artemis, 2020).

CEA trends around the world

For many, CEA conjures up images of hi-tech, highly automated variations in sterile, purpose-built buildings or repurposed spaces in wealthy cities of developed countries. Certainly, these forms attract both media attention and investment. Kaufmann's (2018b) rapid global tour of initiatives includes rooftop farms in Belgium and Massachusetts, USA; salad production in repurposed bomb shelters in London, UK; vertical units on office walls in Australia and Singapore; hydroponics using desalinated seawater in Australia, Oman, Somaliland, and Tenerife; floating greenhouses and aquaponic barges in Hungary and Spain; caviar production from aquaponic-raised sturgeon in the UK; and more.

Japan has been dubbed the 'epicenter' of vertical farming, with a reported 200 'plant factories' each producing 20,000 heads of lettuce per day (Drechsel and van Veenhuizen, 2018). Alongside Japan, the State of Vertical Farming 2016 report (Brin et al., 2016) sites North America at the forefront of commercial ventures in this sub-set of CEA, with an emphasis on large-scale, high-volume models in the US and smaller start-ups in Canada. Europe was trailing in operational terms (with more operations scheduled to come online from 2017) but with considerable technological prowess due to the European headquarters of several equipment and technology leaders. China, too, earned special mention for state-sponsored development of lower-cost vertical farming technology. As of 2016 there were thought to be between 110 and 160 vertical farms in mainland China, and a further 112 in Taiwan.

While industrialized countries have a march on advanced technology, the articles in the special issue of Agriculture for Development on CEA (Kaufmann, 2018a) bore witness to activity in parts of Africa – notably in Egypt (large-scale greenhouse projects in cooperation with Dutch businesses) and South Africa, 'considerable' presence in Kenya, and a clutch of cases in other countries such as Nigeria, Namibia, and the challenging environment of Somaliland (Kaufmann, 2018b; Ozor et al., 2018; Wainright, 2018). The State of Vertical Farming 2016 report (Brin et al., 2016) also identified 'surging interest' in both ground-based and vertical soil-less farming[2] from Indian farmers, entrepreneurs and investors. The authors identified 30 companies practicing soil-less farming in India, including seven commercial vertical farms, but called for in-country fieldwork to know the full size and potential of the market. It would also be interesting to assess the potential fit between CEA and Prime Minister Modi's Smart City concept (The Economic Times, 2016).

In preliminary research for this report based on analysis of online information, Kumudu Vinodya Herath examined 19 CEA enterprises in the Global North and 19 in the Global South[3]. Of these, cases from industrialized countries in Asia and Africa are summarized in Box 1[4]; cases from low- and lower-middle income countries were included in the study in the next chapter.

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[2] Brin et al. (2018) use the term 'vertical farming' for all forms of soilless farming in India because there is no firm distinction between ground-based and vertical farming in the country at present.

[3] In the assessment the Global North was represented by economically developed and technologically advanced countries (USA, Canada, Netherlands, Singapore and South Korea) and the Global South was represented by economically and technologically less advanced countries (India, Sri Lanka, Vietnam, Kenya and Nigeria).

[4] Two cases identified by Herath, and AgriProtein in Singapore are excluded from Box 1. Pacific AgroFarm in Singapore is excluded because the website states the company has permanently closed. AgriProtein in South Africa is excluded as its UK parent company entered administration.

BOX 1 | Example cases of CEA in industrialized countries in Asia and Africa*

Sky Greens, Singapore
Sky Greens began commercial operations in 2012 and is described as an organic and zero carbon vertical farm. The farm is housed in a purpose-built glass structure, consisting of rotating tiers of growing troughs that are mounted on aluminium A-frames, to use natural sunlight. A-frames can be up to 9 metres high, with 38 tiers. The farm has a total of 600 m^2 of growing space.

The troughs can be customised for different crops, and for soil and hydroponic growing. The tiers rotate to ensure plants get uniform sunlight, irrigation and nutrients. Rotation is powered by hydraulic system (using flowing water and gravity), with only 40 W electricity (equivalent to a light bulb) is needed to power a 9 m tower, and 0.5 litres of water for a 1.7-ton vertical structure. Nutrient delivery is via flooding method, and water is recycled through the system.

Sky Greens also has a patented mobile cold chain management system, for vacuum cooling, storage, and transportation in one unit.

With Green Trade Financing from UOM, Sky Greens has expanded through a micro-farm franchise model. (Source: Skygreens, 2014).

Oh's Farm, Singapore
Oh's Farm is a family-run business that began in 1991 and now has 50 employees, on an area of 2.44 ha containing 220 greenhouses. The farm produces a wide variety of exotic vegetables and culinary herbs in both vertical and mono-layers using hydroponics (dynamic root floating technique) in greenhouses that are covered in plastic sheeting and netting. The only light is natural sunlight. The farm claims to use 6 times less water than traditional farms, with nutrient solution recycled via 40 nutrient tanks, each serving six greenhouses.

The main markets are direct to consumer and wholesale distribution, as well as local hotels and restaurants. The farm produces 1-1.5 ton of vegetables per day. (Source: Singapore Farming, 2014).

ComCrop, Singapore
ComCrop is a rooftop farming concept deployed at several sites in Singapore. The idea is to use marginalised spaces to grow leafy greens and herbs, using (unspecified) hydroponic methods. The plants are grown in vertical troughs and are open air (with a small, slanted roof over each structure). Lighting is natural sunlight only. The farm has 560 m^2 of growing space, producing 150 kg a month. It employs local residents and works with social organisations to provide opportunities for marginalised people (including processing of basil leaves into a pesto sauce). (Source: ComCrop, 2021)

NextOn, DangjaeTunnel, South Korea
The NextOn indoor farm was established in 2017 in a disused highway tunnel, which closed in 2002. Using vertical shelves, the 600 m tunnel contains 2300 m^2 of hydroponic (unspecified technique) growing space for salads, leafy greens and strawberries. Lighting is from LEDs. Temperature is controlled at between 10 and 22C, and there is artificial air conditioning. Some reports state that music of Beethoven and Schubert is piped into the facility to stimulate plant growth. Production is around 19,000 kg/month, for the high end and expert markets including functional foods and pharmaceuticals. (Source: Doran and Pisa, 2019).

MetroFarm, South Korea
MetroFarm is a 10-year collaboration between transportation operator Seoul Metro and Farm 8, an agricultural innovation company, to produce 30 different types of vegetables in disused commercial areas of underground spaces. Production is via (unspecified) hydroponic systems on vertical trays, using LED lighting and controlling temperature, humidity and CO_2. The first installation was in Sangdo station in 2019, with plans to expand to three other stations by the end of 2020. The venture produces around 1000kg of vegetables per month, much of which is served in in-station restaurants. Some is also sold externally, including exports of long shelf-life crops (e.g. paprika) to Japan. Revenue is approximately USD 75,000 per month. (Source: Moon, 2020).

*As identified in preliminary research by Kumudu Vinodya Herath.

It is already clear from the documented experiences with CEA in less developed countries that operational parameters must be adapted to local environmental conditions, technological capacity, infrastructure, and policy support (Ozor et al., 2018). In her preliminary research Herath identified significant differences in practices used in 17 CEA enterprises in the Global North and 17 in the Global South, (see Annex 1 for full methods, data sources and data tables).

Operational scale: 53% of the Northern enterprises were medium-scale operations (501 to 1000 m^2), 35% were large scale (over 1000m^2), and 12% were small scale (under 500 m^2). In the South, on the other hand, there were considerably more small-scale initiatives (47%) than medium (29%) and large-scale (24%). (See figure 1.)

Use of growing space: In the North, vertical use of space was more popular than mono-layer farming at all three scales, whereas in the south there were more small-scale vertical farms, but mono-layer was preferred for medium- and large-scale operations. (See figures 2 and 3.)

Production efficiency: Vertical farms reported higher production efficiency in terms of (kg/month per m^2) than mono-layer farms.

Growth media: Hydroponic systems were most popular across all operational scales of CEA in both geographies, followed by soil-based and aquaponic (no cases of aquaponic or aeroponic systems were identified among the Southern respondents). (See figures 4 and 5.)

Facility type: Different structures were employed in both geographies, but in the North there was a greater variety, with examples of purpose-built premises (24%), closed rooftop installations, open rooftop installations, basements, repurposed old buildings, shipping containers, polytunnels/net houses, and other spaces. In the South, low-cost polytunnels and net-houses were by far the most popular (53%), followed by purpose-built facilities, shipping containers, repurposed old buildings, and others. (See figure 6.)

Energy use: In view of the complexity of artificial climate control in CEA, artificial lighting was used as a proxy for energy use. In the Global North, which includes more temperate climates where enclosed growing spaces are more common, 53% of cases used artificial light, 35% natural light, and 12% used both. In the South, where polytunnels and net-houses that admit sunlight are more common, 71% of cases relied on natural light and 29% on artificial light. (See figures 7 and 8.)

Motives for adopting CEA

It is apparent that the motivation for adopting CEA varies depending on the context. Operators of sophisticated systems tend to claim to be promoting sustainability and food security (see discussion in 3.3), but Drechsel and Veenhuizen (2018) point out that these systems are only viable where consumers are willing to pay a premium for ultra-fresh produce that has been grown without pesticides, or where potential contamination creates safety concerns about conventional vegetables. The latter has been a particularly potent driver in Japan, especially in the wake of the 2011 Fukushima disaster, and in China (Brin et al., 2016; Newbean Capital, 2016). In less developed country contexts, including Africa and parts of Asia, on the other hand, demand for CEA-grown produce – as opposed to conventional, outdoor grown produce – may not be the primary driver. Rather, in the collection of articles in Kaufmann (2018a) CEA is seen as a potential solution to a complex of issues relating to agricultural viability and the wider food system, including:

- 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;
- enabling women and other disadvantaged groups to grow food and access economic and social opportunities.

These articles form part of the body of literature on the putative contribution of CEA to the sustainable development objectives associated with SAI that was reviewed in the study.

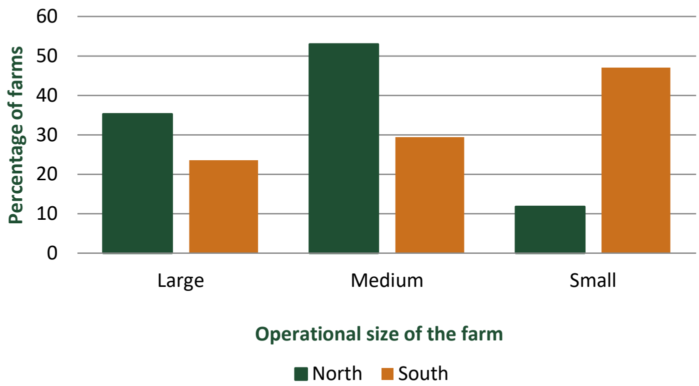

Figure 2: Operational size of CEA operations in Global North and South

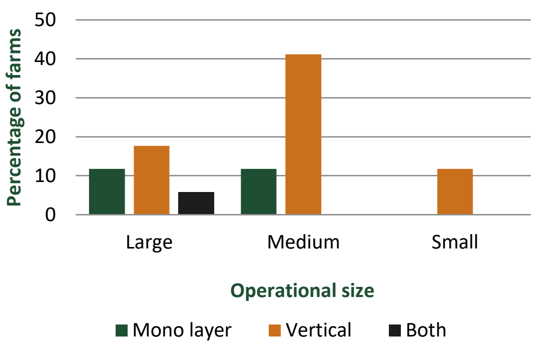

Figure 3: Use of growing space under different operational scales in Global North

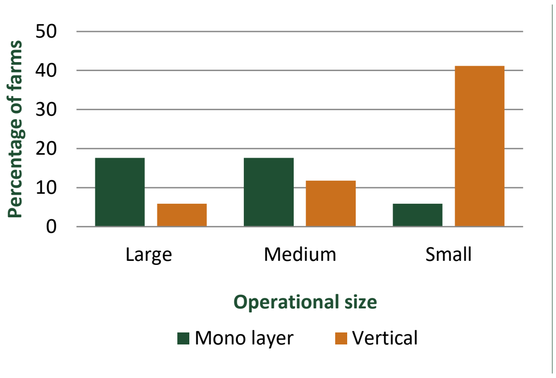

Figure 4: Use of growing space under different operational scales in Global South

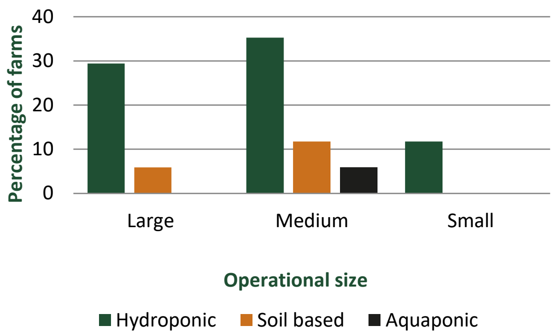

Figure 5: Use of different growth media or growing techniques of the cases from Global North

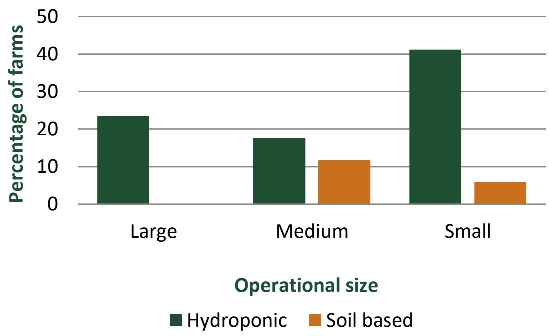

Figure 6: Use of different growth media or growing techniques of the cases from Global South

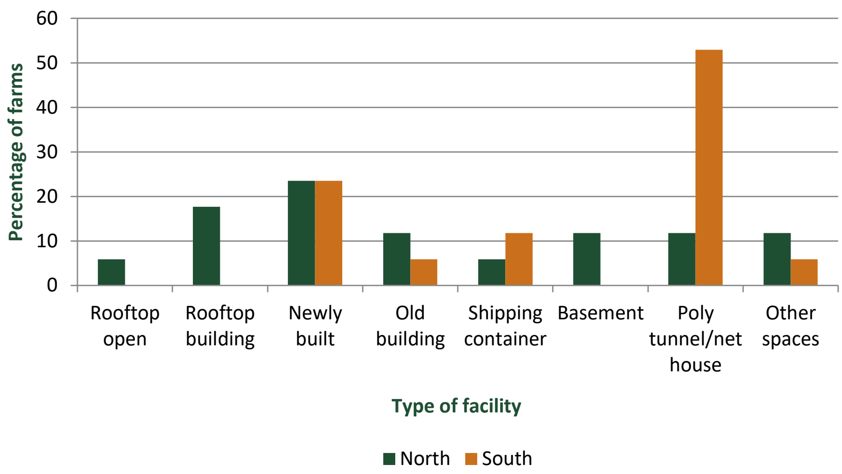

Figure 7: Types of spaces used in CEA in the assessed cases from Global North and South

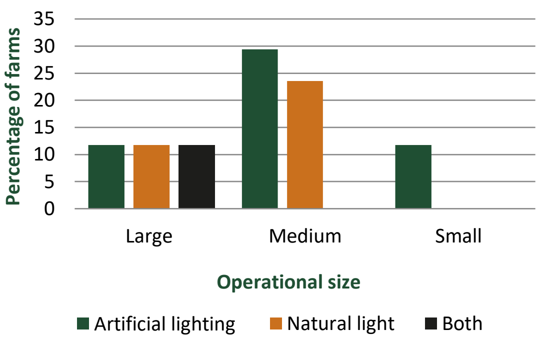

Figure 8: Use of artificial light in Global North

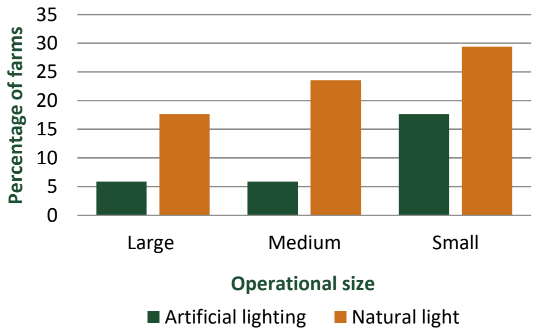

Figure 9: Use of artificial light in Global South

3. The study

Study methodology

The study was conducted in two parts.

Part one consisted of a literature review of both academic and grey literature discussing the putative benefits of CEA in relation to three main areas of sustainable development: food security; poverty reduction and social equity; and resource use and the natural environment. Information from the literature review contributed to answering research question 2.

The grey literature was identified by searching for the terms ‘Controlled Environment Agriculture’ and each of the sustainable development areas in Google. Academic literature was identified using the same terms in Elsevier’s Science Direct Database and Google Scholar. Additional literature was identified from the reference lists of papers identified in the initial searches. Due to the lack of formal definition of CEA and the use of alternative terminology and similar concepts (see footnote 1 above), the literature review included results on vertical farming, plant factories and ‘innovative urban agriculture’. Although the focus of this report is low- and lower-middle income country contexts in Africa and Asia, the literature review included information and insights from high-income countries. This is because the five areas of development are also relevant to those contexts, albeit with different degrees of urgency and nuance, and secondly because some CEA technologies are (or will be in the future) suitable for transfer to low and lower-middle Asian and African contexts, with some adaptation or as costs come down.

Part two consisted of document analysis and semi-structured interviews relating to cases of CEA in low- and lower-middle income country contexts. Information from the document analysis and interviews was used to answer all three of the research question 1. For research question 2, it provided confirmation and new complementary insights to those obtained from the literature review.

Documents (and videos) relating to 19 cases of CEA that were identified by Herath were retrieved, and their content analyzed for their relevance to the three questions addressed in this study. Content analysis was also carried out on 7 additional cases identified by the present authors. The names, locations and basic information of all cases are set out in Table 1 and 2; supplementary information on the interview cases is in Annex 2).

Next, semi-structured interviews were conducted with 12 CEA operators and value-chain actors (see Annex 2 for brief descriptions of the interviewees’ activities). The decision was taken to interview practitioners/operators in two African countries (Nigeria and Kenya) and two Asian countries (India and Sri Lanka) to be able to cross-check findings between country contexts. Potential interviews were identified initially from the list drawn up by Herath (see Annex 1); the list was augmented by further web searches where additional/alternative subjects were required (due to non-response), and deliberately included some equipment and training providers (who also run their own personal farms) in anticipation that they would know the state of the CEA market in their local area. Attempts were made at gender balance between interviewees but the majority of practitioners identified were male and of the females several did not respond to interview requests. As a result, nine interviews were with men, two were with women, and in one case a man and a woman together.

Interviews were conducted by telephone or an online communication platform (e.g. Skype, WhatsApp, Zoom), and lasted between 30 and 45 minutes. The calls were recorded and transcribed and the content analyzed.

In one case, where time zone constraints made it impossible to schedule an in-person interview, the interviewee received the written questions via email and responded with a voice recording that was subsequently transcribed; clarifications were obtained via email. The interview guide is provided in Annex 3.

The majority of interviews were conducted in English. Three interviews with small-scale operators in Sri Lanka were conducted in Sinhala and the responses were translated into English. Interviewees were given the opportunity to participate on an anonymous basis, but all agreed for their name to be used in the report.

Table 1: Case studies of CEA in low- and lower-middle income countries in Africa and Asia (horticulture)

Name	Country	Facility	Growth medium	Vertical/ mono	Lighting	Interview
Herbivore Farms	India	Repurposed building	Hydroponic	Vertical	Artificial	No
Letcetra Agritech	India	Purpose built	Hydroponic	Vertical	Artificial	No
Acqua Farms	India	Purpose built	Hydroponic	Vertical	Natural	No
CRAFT Compounds Ltd	India	Greenhouse/ polytunnel/ nethouse	Hydroponic Aquaponic	Mono and vertical	Natural	Yes
GreenOx	Vietnam	Shipping container	Hydroponic	Vertical	Artificial	No
Lanka Salad Company	Sri Lanka	Greenhouse/ polytunnel/ nethouse	Hydroponic	Mono	Natural	Yes
Honest Greens	Sri Lanka	Purpose built	Hydroponic	Vertical	Artificial	Yes
K. Chaminda Rangana	Sri Lanka	Greenhouse/ polytunnel/ nethouse	Hydroponic	Mono	Natural	Yes
Jayanath's Farm	Sri Lanka	Greenhouse/ polytunnel/ nethouse	Soil	Mono	Natural	No
Renuka's Farm	Sri Lanka	Greenhouse/ polytunnel/ nethouse	Hydroponic	Mono	Natural	No
Sunil's Farm	Sri Lanka	Greenhouse/ polytunnel/ nethouse	Soil	Mono	Natural	No

Name	Country	Facility	Growth medium	Vertical/ mono	Lighting	Interview
H&D Farm	Sri Lanka	Greenhouse/ polytunnel/ nethouse	Hydroponic	Mono	Natural	No
S. Ranasignghe	Sri Lanka	Greenhouse/ polytunnel/ nethouse	Hydroponic	Mono	Natural	Yes
P.K. Samarasinghe	Sri Lanka	Greenhouse/ polytunnel/ nethouse	Hydroponic	Mono	Natural	Yes
Can Ya Love	Kenya	Other spaces	Soil	Vertical	Natural	No
Hope Wanjiru's Farm	Kenya	Greenhouse/ polytunnel/ nethouse	Hydroponic	Vertical	Natural	No
Greenthumbs CBS	Kenya	Greenhouse/ polytunnel/ nethouse	Aquaponic	Mono	Natural	Yes
Miramar International Farm College *(farm and training provider)*	Kenya	Greenhouse/ polytunnel/ nethouse	Hydroponic	Vertical	Natural	No
Kabete Rehabilitation School	Kenya	Greenhouse/ polytunnel/ nethouse	Hydroponic	Vertical	Natural	No
Hydroponics Africa *(equipment and training provider)*	Kenya	Not applicable	Hydroponic	Vertical	Natural	Yes
BIC Concepts *(equipment and training provider)*	Nigeria	Greenhouse/ polytunnel/ nethouse	Hydroponic	Vertical	Natural	Yes
Soilless Farm Lab *(farm and training provider)*	Nigeria	Greenhouse/ polytunnel/ nethouse	Hydroponic	Vertical	Natural	Yes
Fresh Direct	Nigeria	Shipping containers	Hydroponic	Vertical	Artificial	No
Save Our Agriculture (equipment supplier)	Cameroon	Greenhouse/ polytunnel/ nethouse	Aquaponic	Mono	Natural	No

Name	Country	Facility	Growth medium	Vertical/ mono	Lighting	Interview
Vertical Gardens (equipment supplier)	Kenya	Greenhouse/ polytunnel/ nethouse	Hydroponic	Vertical	Natural	No
Vertical and Microgardening (equipment supplier)	Uganda	Open	Soil (vermi-compost)	Vertical	Natural	No
AliFarms Group	Rwanda	Not specified	Hydroponics	Vertical	Natural	No

Table 2: Case studies of CEA in low- and lower-middle income countries (Black Soldier Fly)

Name	Country	Facility	Space	Medium	Capacity	Interview
Forward (research project)	Indonesia	Not available	424m^2	Fruit and veg market waste	0.2 tonnes live larvae/day	No
Ento-prise (research project 2014-2016)	Ghana	Not available	212m^2	Fruit and veg market waste	About 0.006 tonnes of dried larvae and 0.075 tonnes of biofertilizer per day	No
Sanergy	Kenya	Purpose built	Not available	Human excreta	Not available	No
Exocycle	India	Re-purposed building	Not given; 3000 plastic trays	Fruit and veg market waste; rendered chick carcasses	3 tonnes of live larvae	Yes
Segel Oik Ventures	Kenya	Purpose-built greenhouse	Not given	Pig manure, potato peelings	220-250kg live larvae per day	Yes

Sources: See Annexes 1 and 2

CEA technologies most suited to low- and lower-middle income contexts

The study revealed uptake of a diverse range of CEA technologies, and their adaptation to particular economic, social, and environmental circumstances.

Hydroponics and aquaponics

Among case studies in all country contexts the most common **structures** for CEA crop production are greenhouses and polytunnels, with plastic or polythene roofs. In some cases, the sides were covered with nylon or fabric netting to provide ventilation.

'The beauty about this farming is it doesn't have to be all singing and dancing. It is getting the relevant technology to the ground… Relevant means fit for purpose and affordable'. (Charlie Hancock, The Lanka Salad Company, Sri Lanka).

The main considerations in choosing greenhouses and polytunnels were the ability to create an optimum growing environment, use of natural light, protection from heavy rains, keeping out pests and disease, and cost. Additional considerations mentioned by CRAFT (India) are the need for structures to withstand weather conditions in all seasons of the year (in India the monsoon season, the humid summer, and the relatively cool winter), and to be manageable within the local skillset if the objective is for local farmers to adopt the new techniques. The latter point was echoed by The Lanka Salad Company: greenhouses, and the relatively simple systems they house, can be quite easily repaired in case of breakdown.

The downsides of greenhouses are occasional fungal attacks, excessive heat, and degradation of the polythene covering. One small-scale Sri Lankan grower opted to use UV-resistant polythene to protect against material degradation over time.

Generally, greenhouses and polytunnel structures were easy to obtain locally, with the exception of Nigeria, where greenhouses are not yet popular; they are imported and relatively expensive. In some instances, however, hydroponic units were installed outside of greenhouses, depending on crop varieties and space constraints. While most of BIC Farm Concepts' production in Nigeria is in greenhouses, around 5% is outside under shade netting, and 1% is outside with no shade. Similarly in Kenya Hydroponics Africa supplies hydroponic units that can be installed in a variety of enclosed or open settings, including the smallest unit that can be mounted on the wall of a building for those with no land.

Among the interviewees, the outlier to the greenhouse trend is Honest Greens, which grows vegetables inside a purpose-built building with LED lights and air conditioning. However, secondary data was reviewed relating to several other cases where vegetables are grown hydroponically in indoor facilities, in shopping containers (Fresh Direct, Nigeria; GreeOx, Vietnam); re-purposed building (Herbivore Farms, India); purpose-built buildings (Letcetera; Aqua farms, India) (see Table 1 above). The motivations for using entirely enclosed buildings in these contexts were given as the ability to completely control the environment, enabling year-round production and cultivation of non-native crops; and complete exclusion of pests. In the case of Fresh Direct, the ready availability of shipping containers in urban areas was also a factor. Other interviewees pointed to the downsides: excessive energy use for cooling and ventilation, and the need for on-call technicians to repair system breakdowns.

Among the greenhouse growers, the **environment control parameters** were determined with cost, minimal energy use, and local resources/infrastructure in mind. In particular, Peter Chege of Hydroponics Africa (Kenya) emphasized the need for Western hydroponics methods to be 'simplified' for African contexts. In the enclosed exploitations, on the other hand, there was no explicit mention of the need to keep energy use to a minimum. Rather, control parameters were selected to provide the optimum conditions. This suggests a trade-off – conscious or otherwise – between the environmental impacts of energy use and the ability to produce higher, consistent yields, sales of which compensate for the costs of high energy use.

In both greenhouse and indoor models, there is a general preference for **vertical use of space** over mono layer farming, to optimize use of natural light (with the exception of the greenhouse growers in Sri Lanka). Greenthumbs CBO's aquaponic farm the vegetables are grown in raised beds, but in retrospect the partners believe they should have installed vertical or pyramid structures to have a larger growing area while still making optimal use of sunlight. Vertical farming is also considered suitable at various scales, with companies selling A-frame or other vertical kits for household level, with scalable models for various scales of commercial growing (Hydroponics Africa, Kenya; Vertical Gardens, Kenya; Vertical and Microgardening, Uganda).

As for temperature control, the small-scale growers in Sri Lanka use no artificial cooling. The Lanka Salad Company uses a pad and fan system[5] to cool its greenhouses, while Honest Greens keeps its building cool using air conditioning.

In Africa, where circulation fans are rarely used, natural ventilation is likely to be built into structures – such as 2-metre-high side nets, or a 'gothic' greenhouse with pointed roof and a vent for hot air to escape (Debo Onafowora, Nigeria). Peter Chege (Hydroponics Africa, Kenya) reported using of double-layer shade nets in Northern Darfur enabled the temperature to be reduced by 15°c – from 40°c to 25°c – enabling cultivation of leafy greens and tomatoes.

Interviewees did not widely discuss use of AI **sensors** to inform environmental control, although on its Mystiq Garden website, CRAFT (India) states that is uses sensors for measuring air and soil temperature, humidity, atmospheric pressure, monitoring pH levels, ammonia, nitrate and nitrite levels. The sensors are monitored using mobile phone applications. It also states that it uses drones and robots to improve data collection. Samson Ogbole (Soilless Farm Lab, Kenya) was frustrated by lack of access to sensors to monitor temperature and humidity, and tiny drones to monitor crops in vertical farms.

Most of the hydroponic operators interviewed use **irrigation/nutrient methods** that require little or no electricity to pump the solution – that is, ebb and flow, drip irrigation, and the Kratky method. NFT was not generally favored as it requires constant power to pump nutrient solution around the plant roots, which increases operating costs, particularly in places where a generator would be required because 24-hour mains electricity is not guaranteed. The only operators interviewed who were using NFT were Honest Greens and The Lanka Salad Company in Sri Lanka, both of which are corporate suppliers to the high-end produce markets. The Lanka Salad Company emphasized the need for pure water, which can be obtained using reverse osmosis. For the case studies that were examined using documentary sources, the type of hydroponic technique was not specified.

[5] Pad and fan systems use exhaust fans to pull air through evaporative cooling pads.

For the same reason of expensive, inconsistent electricity supply, Soilless Farm Lab (Nigeria) abandoned an early venture into aeroponics. CRAFT (India) also acknowledged the need for 24-hour electricity (with a back-up battery in case of outages) as an expensive drawback to its aquaponics operations, where water must be kept moving around fish in high-density tanks. Fresh Direct (Nigeria) was the only case relying on electricity to control the environment that has experienced problems due to outages. However, these seem to be relatively surmountable compared to the challenges of growing food outside the city and being unable to transport it to market due to fuel shortages and lack of cold storage.

Operators in all contexts sought out cheap, locally-available materials as **substrates or growing media**: coco peat and coco chips in India; coco peat in Sri Lanka; rice hulls and coco coir in Nigeria; pumice in Kenya. In Kenya, Peter Chege (Hydroponics Africa) practices 'asset-based community development', which involves determining locally-available assets in every location where he helps people set up hydroponic farms, avoiding imported materials.

Black Soldier Fly (BSF) production

The BSF case studies differ in terms of structure. At Sagel Oik Ventures (Kenya) the BSF operation is based in a purpose-built greenhouse on a concrete base and open sides covered with netting, to optimize the temperature. This constituted the main set-up cost, and a key variable is the quantity of greenhouse paper used.

'Being among the very first people who set up the unit in Kenya there are things that we could have done differently. I don't think it is necessary to put in all the greenhouse paper [polythene covering] but just sufficient. If your area is of around 25°C degrees and above then really you just need the greenhouse sheeting as curtains for the evenings. During the day there is sufficient heat.' (Roseanne Mwangi, Sagel Oik Ventures, Kenya).

The facility of Sanergy is purpose built, but none of the documents examined contained any information on the structure itself or the precise techniques used, with the exception of one blog briefly discussing various methods various methods of harvesting the larvae. Rather, the company places more emphasis on publicizing design of latrines to provide the growing medium.

At Exocycle (India) the BSF operation is housed in a disused deep litter boiler chicken shed, with a concrete structure and two layers of netting over the sides to keep out small flies and birds (especially since Tamil Nadu is notoriously windy). In this case the main set up costs concerned the interior structures and cages for the different stages of the BSF lifecycle.

Exocycle and Segel Oik, and the two research facilities, use similar techniques and materials, with wooden structures for egg-laying, plastic crates for rearing the larvae, and (separate) purpose-built cages for the pupae and adult flies. The main parameters monitored are temperature (optimal mating temperature is 23°C) and humidity (around 50%).

Both Exocycle and Segel Oik are co-located with livestock farms – a pig farm in the case of Sagel Oik and a chicken farm for Exocycle – which gives them privileged access to animal waste (excrement and, in the case of Exocycle, rendered broiler chick carcasses) as a medium/feed for the larvae, as well as providing the respective farms with a source of high-protein feed. They also make use of other nearby waste streams – organic waste from the municipal dump in the case of Excocycle and peelings from a local potato processing facility for Sagel Oik Ventures. The pilot facility established under the

FORWARD project in Indonesia, meanwhile, is located at a wholesale market for ease of access to waste material, although there is evidence that volumes are inadequate for commercial viability.

Contribution of CEA to sustainable development

Food security

Contributions identified in the literature

The term food security infers the state of having reliable physical, social, and economic access to a sufficient quantity of safe and nutritious food. This means that an assessment of the contribution of CEA to food security should include not only crop yields, but also what crops are produced; the consumer groups they are produced for; affordability; and consumer acceptance. These factors are crucial to determining whether CEA results in healthier diets, and especially whether people with micro-nutrient deficiencies benefit (Pinstrup-Andersen, 2018).

Crop yields: CEA has the potential to deliver high yields of fresh produce on a fraction of the acreage of traditional soil-based open agriculture. According to respondents in Artemis's State of Indoor Farming Survey 2020 (Artemis, 2020), on average indoor vertical farms can produce 9x higher yields per square foot than outdoor farming (although the multiple depends on the number of layers, since each adds to the production per unit footprint), mid-tech glass/poly greenhouses 14x higher, and container farms 29x higher (Artemis, 2020). The potential to produce fresh, healthy food in significant quantities in the heart of built-up, low-income neighborhoods, without reliance on complex and vulnerable rural-urban supply chains, led Pridmore (2018) to CEA as 'game-changing' in efforts to address urban food and nutrition insecurity. CEA can also extend the growing season – or even, in completely enclosed systems, enable year-round cultivation, with protection from adverse weather events (Mytton-Mills 2018; Jensen 2002).

What crops. In high-income, industrialized countries, the primary crops in CEA production are leafy greens and herbs, and other high-value vegetables such as tomatoes, peppers, and squash, grown in vertical farming systems (Wainright, 2018; Goodman and Minner, 2018). This crop selection is determined by economic expediency rather than nutritional value: their short production cycles enable quick turn-overs; they can be stacked in multiple vertical layers; and their perishable nature means there is value in growing them close to their place of consumption (Agrilyst, 2017). Proponents assert that many more foods could be produced in vertical farming systems, and intense R&D efforts aim to identify suitable cultivars on a continuous basis. Some authors have expressed optimism over the cultivation of nutritious staples like soy, wheat, rice, and potatoes in CEA systems (Despommier, 2019; Germer et al., 2011), but the literature search showed up no public data to demonstrate the economic and environmental viability of large-scale CEA production of these crops. CEA could, however, provide a complementary supply chain (e.g. Despommier, 2019; Pinstrup-Andersen, 2019), which could provide a buffer in case of extreme weather events affecting conventional produce (Garcia-Caro Briceño, 2018) or other supply chain failures that result in supply-demand gaps and rising prices (Ngongi et al., 2018). Moreover, there are reports of growing mixes of grains, such as barley, wheat, and maize, in hydroponic systems for animal fodder to reduce land use pressures and competition with human food sources (e.g. Wanzala, 2019; FAO, 2015; Sinsinwar and Teja, 2013). CEA techniques (especially hydroponic) have also been used for breeding new seed varieties, including for wheat (e.g. Du Toit, 2005), rice, and potatoes (e.g. Tunio et al., 2020) and for raising rice seedlings to be transplanted to paddy fields (Saxena and Upadhyay, 2019).

For whom: Most of the literature on the target consumers for CEA produce identifies affluent, middle-class customers who are prepared to pay a premium for fresh, pesticide-free produce, or produce that has been grown away from potential sources of contamination that could jeopardize food safety (such as following the Fukushima disaster in Japan). In 2013, Wilkins (2013) reported little evidence of vertical farming helping to feed hungry and food insecure people who typically lack access to affordable, quality vegetables, in either developed or emerging economies. This finding was echoed by Goodman and Minner (2019) whose assessment of CEA in New York concluded that it brought no benefits to the city's almost 3 million food insecure residents.

Affordability. At present CEA produce in high-income countries is sold at a premium; for example, green leafy vertically-farmed vegetables in Singapore are around 10% more expensive than their imported conventionally-grown equivalents (Benke and Tomkins, 2017). The main justification is that the price must reflect the high start-up costs of CEA farming. A 10-level vertical farm in Sydney or Melbourne, Australia, would have an estimated start-up cost of US$317 per m^2 of arable land, for instance, even without construction and fit-out (Benke and Tomkins, 2017); no comparable analysis was identified for technologies in low- and lower-middle income countries. The margin of difference with conventionally-grown produce may narrow as the initial investment is amortized, productivity increases, and new, cost-effective technologies become available (see discussion below on LED), but no models have been identified to predict when this might happen. Until such time as it is economically viable to produce vegetables via CEA without charging a premium, it is highly unlikely that low-income consumers with micro-nutrient deficiencies will benefit (Pinstrup-Andersen, 2018). Even after economic viability is achieved, price parity will depend on whether producers are motivated primarily by social justice or commercial gain.

Consumer acceptance. Ultra-fresh, pesticide-free hydroponic vegetables have been positioned as aspirational goods in high-income countries, but Despommier (2019) anticipates that demand will trickle down to middle- and low-income customers over time (although probably not so far as the poorest urban residents in slums). Other have noted a certain amount of skepticism among would-be consumers, such as a perception that vegetables grown without soil are 'Frankenfoods' (Benke and Tomkins, 2017). Kagan and Riemenschneider (2018) acknowledge consumer doubts over nutritional quality of hydroponic vegetables compared to soil-grown, while Nwosisi and Nandwani (2018) anticipate that some consumers will be put off by the idea of aquaponic vegetables being fertilized with fish effluent. This latter aversion, which is rooted in food culture or safety fears, will have greater impact on acceptance among food insecure consumers than nutritional equivalence.

The above discussions broadly support the conclusions of Armanda et al. (2019), who reviewed academic and grey literature on the potential of 'innovative urban agriculture' (IUA)[6] to contribute to food security and environmental management, including data from 18 practitioners in the US, Europe and Asia. They concluded that there is some positive evidence relating to the ability of IUA technologies to increase local food supply, strengthen the food value chain, and employ sustainable practices, but rigorous research data are lacking.

[6] Armanda et al. (2019) did not look exclusively at CEA, but their definition of IUA included both open and closed systems using 'indoor agriculture, remote sensing, vertical agriculture, hydroponic, aeroponic, aquaponic and soilless agriculture, precision agriculture, and other novel technologies. This includes both open and closed systems'.

Contributions from the case studies

Almost all the CEA operators interviewed claimed that their CEA activities contributed to their food and nutrition security in some respect in the present or predicted that it would do so in the future.

Present contributions to food security were not framed in terms of increasing food access and availability (unsurprisingly since none of the interviewees operate in a context of current food scarcity). Rather, the case studies highlighted improved food quality and nutritional value, and supporting affordability by reducing price fluctuations. Confirming observations from the literature review, the question of affordability is complicated by a tendency to pursue high-end, niche markets, sometimes for exotic varieties that do not form part of the local diet, to off-set high start-up and running costs.

In the future, there are expectations that technological improvements will lead to CEA grown produce breaking out of the high-end niche, with more local varieties and affordability for lower-income groups. There was an expectation among interviewees that CEA will make a greater contribution to access and availability aspects of food security in the face of climate hazards and depleted workforce of conventional farmers.

The following paragraphs provide more detail on the interviewees' insights related to food security.

Food quality and nutritional value

Vegetable growers in India and Nigeria decried the poor quality and reduced nutritional value of produce that has been transported hundreds of kilometers from its place of production to market. They claimed that hydroponic/aquaponic vegetables offer nutritional advantages because they are grown closer to market and are therefore fresher. They also referred to vegetables grown without use of pesticides as healthier – particularly produce from fully indoor CEA operations that are pest-free (such as Herbivore Farms in India) and from aquaponic systems, which are guaranteed to be pesticide-free since the addition of chemicals would kill the fish.

BSF farmer Rosanne Mwangi (Segal Oik Ventures, Kenya) also said her activity contributes to improved food quality and nutrition because:

'The quality of the food that comes out from the BSF-fed animals – the chickens especially – is very high. The layers lay quite a bit of eggs, so people are happy with the product. I don't know whether it is zero hunger but it contributes to giving quality food that is beneficial for human consumption.'

Affordability

The limited, non-traditional crop selection, coupled with the exclusive market, means the growers in India and Sri Lanka do not currently support to food and nutrition security. However, interviewees from both countries presented a narrative of building future food security.

CRAFT Compounds (India) expressed an ambition to lower their prices as the cost of technology comes down, drawing parallels with the telecoms sector, in which mobile phones became more affordable over time.

'We are hoping [hydroponically/aquaponic vegetables] will not be just for the rich but will be for people who are really conscious of their health'.

The Lanka Salad Company commented that bringing prices down would give them a 'larger addressable market' – that is, middle-income Sri Lankans. Honest Greens said that supplying premium leafy greens allows them to be profitable in the short term, while continuing trials with local varieties with a view to their technological and economic feasibility in the future.

In terms of affordability, there is no evidence that CEA produce exerts downward pressure on overall food prices, as supply of conventional produce is already able to meet demand on local markets.

However, some growers defined affordability in terms of enabling constant year-round prices with no seasonal fluctuations; since crops are protected from weather variables, the growing season is longer (or, in the case of completely enclosed structures, year-round). These constant prices would be above the in-season lows but below out-of-season highs.

'If you cannot crash the price of food, at least keep it constant so that people can plan with their resources.' (Samson Ogbole, Soilless Farm Lab, Nigeria)

Similarly, a representative of Honest Greens (Sri Lanka) cited price variability of between LKR 200 and 2500 per kg (between US$1 and $12.50) for some vegetables, and said affordability 'is not just about bringing other prices down… but also in the context of other prices going up'.

Crop selection and target markets
Price-point is closely connected to target consumers and the varieties grown to appeal to them. The hydroponic/aquaponic growers in Kenya and Nigeria focus on vegetables that form part of the local diet across all income groups (e.g. tomatoes, peppers, spinach, cabbage, and other leafy greens). Whether sold on local markets or to 'niche' markets such as hotels, the price is the same as for soil-grown produce.

'We do not have a market yet that is dedicated to "I want hydroponic products". Even when we sell to a niche market, we are just selling it as regular products grown in a greenhouse. We are not charging extra because it was grown without soil.' (Samson Ogbole, Soilless Farm Lab, Nigeria)

This inability to command a premium was echoed by Peter Chege of Hydroponics Africa (Kenya). The implication of the word 'yet' in the above quote is that a higher price is desirable, and might be possible in the future once hydroponics are better known and understood as a pesticide-free production method. This may run counter to building food security through increased affordability.

In India and Sri Lanka, on the other hand, hydroponic/aquaponic produce currently sells at premium prices. Through its consumer brand Mystiq Gardens, CRAFT Compounds (India) offers both traditional and 'exotic' salad vegetables, which they sell through an online subscription service or up-market retail at a price that only the most affluent 1% of urban residents can afford. Both The Lanka Salad Company and Honest Greens in Sri Lanka target the high-end retail market (and, prior to the Easter bombings and Covid-19 restrictions, the tourism sector), the lettuce and other leafy greens. The three Sri Lankan polytunnel operators grow cucumbers and bell peppers that do not form part of the local diet but are destined as garnishes or table decorations in the food service sector.

Climate change
A representative of Honest Greens also raised the likelihood of food security being impacted by conventional crop failure due climate change, coupled with increasing demand from growing populations in the coming years. They propose proliferation of CEA as a way to protect crops from

both sudden climate events and incremental changes in growing conditions. Franchise operations situated close to markets might also protect against supply chain disruption.

Farming workforce

Another way in which the case study evidence indicated CEA might bolster future food security is by interesting young people in farming. At present the average age of farmers in many countries is 60+ years and traditional, outdoor farming is regarded as an undesirable career for their descendants. This leads to serious concerns about the ability of rural farming workforces to produce enough food to meet demand.

‘60% or more of our population are young people who are not interested in farming, but the moment they saw soil-less farming it was like “White collar farming? I can farm without soil? And so, I don't have to look dirty to be a farmer?”. That brought a lot of interest from young people wanting to learn about this type of farming.’ (Debo Onafowora, BIC Farm Concepts).

Similar sentiments have been expressed by the founder of Fresh Direct in Nigeria, whose 14-strong workforce includes 10 young women.

Poverty reduction and social equity

Contributions identified in the literature

Poverty reduction in this context is defined as promoting economic growth that will permanently lift as many people as possible over the poverty line (Barder, 2009). From a review of evidence from North America, Europe and Asia, Al-Kodmany (2018) concluded that vertical farming can contribute to poverty reduction by enabling year-round crop production, providing farmers with a secure, constant income, enabling fast recovery of capital costs, stabilizing market price, and maintaining supply chains (Al-Kodmany, 2018). This conclusion is borne out by evidence from the Kenyan flori- and horticulture sectors (e.g. Rajagopal, 2017), albeit with some concerns about fair pay as standard (Leipold and Morgante, 2012; see also Box 2).

Another potential contribution to poverty reduction is through job creation. Although no sources of data on employment in CEA were identified in any context, the Kenyan flower industry, which increasingly uses CEA techniques that being environmental advantages, provides an example of the potential for significant employment, with demand for corporate social responsibility (CSR) and Fairtrade flowers from export markets, such as Europe, redressing poor wages (See Box 2). In industrialized contexts, Benke and Tomkins (2017) anticipate that growth of vertical farming will lead to jobs in engineering, agritecture, biochemistry, biotechnology, construction, and research and development, to be filled from a plentiful pool of university-educated workers. Given that only 51% of vertical farms were profitable in 2017 (Agrilyst, 2017), it remains to be seen whether the job boom will come to pass – and if it does, whether the jobs will be decent. In their assessment of CEA in New York, Goodman and Minner (2019) identified only a small number of new green-sector jobs, with an estimated pay rate below the living wage. In the State of Vertical Farming 2020 survey, Artemis found that 39% of respondents (mainly from North America) plan to implement new technology with the goal of managing operations more efficiently, such as robotics and automation (Artemis, 2020). This may indicate reduced availability of unskilled operational jobs, but job creation along the whole value chain, which will be impacted by increased growing efficiency and output, should also be taken into account.

In medium- and low-income country contexts, CEA could provide opportunities for young people who migrate to cities from rural areas, whether in search of a more profitable, less physical work than traditional farming or because farming livelihoods are no longer viable (Ngongi, 2018). Not only would this prevent new arrivals from falling into poverty, but it would also stem the drain of workforce away from food production. There would, nonetheless, be a need to equip new entrants with the skills for CEA, which differ to those required for open-field agriculture (Ngongi, 2018; Despommier, 2019).

CEA is seen as particularly attractive for entrepreneurs because it is a scalable way of breaking out of cycles of food insecurity, climate vulnerability and unpredictable livelihoods by setting up their own production units (Hawkins-Row, 2018), which require little land to set up on and over time can expand into larger businesses. Chai et al. (2019) note that setting up a BSF farm can generate opportunities for poor households; when combined with animal production it can also help reduce costs, since BSF larvae are cheaper than other animal feeds, such as soybean meal or fish meal. Pfeiffer (2018), meanwhile, identifies particular interest in aquaponics among entrepreneurial young migrants. Starting up is not always straightforward, however. While INMED Partnerships for Children[7] (of which Pfeiffer is CEO) helps entrepreneurs overcome the barriers (e.g. through finance, building technical and administrative skills, and linking to markets), such programs do not exist everywhere. Ngongi (2018) pointed out that youth could be supported to set-up of small greenhouses, which will be beyond the financial means of many, by the many agribusiness/agripreneur programs being set up across Africa, with funding from the African Development Bank, the Alliance for a Green Revolution in Africa and the World Bank, with technical support from the International Institute of Tropical Agriculture. He advocated the development of special agripreneur programs for CEA.

Traditional farm credit institutions tend to ignore small and medium enterprises, while private investors favor start-ups in profitable markets rather than locations with high rates of unemployment and food insecurity (Kagan and Reimenschneider, 2018). While many micro-finance institutions have been created to service smallholders (e.g. Musoni Microfinance in Kenya, One Acre Fund, and many others), no literature was identified to indicate their awareness of the range of opportunities in CEA. More research is needed on the financial and social benefits of CEA entrepreneurship in middle- and low-income contexts, the results of which could be used to make the case to investors – both traditional and microfinance organizations – to provide support new entrants (Kagan and Reimenschneider, 2018).

Some concern has been raised over CEA in cities disrupting broadacre farming by presenting increased competition, thereby increasing poverty in rural areas (Butturini and Marcelis, 2020; Kagan and Reimenschneider, 2018; Pinstrup-Andersen, 2018). However, Kagan and Reimenschneider conclude that current production volumes mean any such threat is still some years away, while Pinstrup-Andersen believes the scale of global micronutrient deficiency means the market can comfortably accommodate both systems, and that they will complement each other. Mytton-Mills (2018), meanwhile, suggests that some traditional farmers could turn over a small part of their acreage to CEA, providing them with a new income stream and securing their livelihood in case of mainstay crop failure.

[7] INMED was originally an acronym for International Medical Services for Health. The organisations is now known as INMED Partnerships for Children.

In addition to providing opportunities for youths moving into urban areas, CEA has the potential to enable other economically, socially, and politically disadvantaged groups – including those for whom land rights are problematic – to grow large amounts of produce in small spaces, both for subsistence and sale. Pfeiffer (2018) and Kagan and Riemenschneider (2018) provide examples of civil society CEA programs that are targeted to women, youth, disabled people, and refugees in or adjacent to conflict zones.

In high-income contexts, the repurposing of derelict buildings can bring new life to neglected neighborhoods, and where indoor farming systems are collective or cooperative enterprises, they can reduce rates of depression and suicide amongst otherwise isolated individuals (Benke and Tomkins, 2017; Lu and Grundy, 2017). They also provide opportunities for community education, skills provision for the long-term unemployed, or volunteer schemes to foster consumer connectedness with their food sources (Al-Kodmany, 2018; Benis and Ferrao, 2018). However, such social benefits have come about as a result of socially-oriented business models and efforts to counter discrimination through policies or programs, such as by providing technical support (in ways, locations, and at times that suit the target recipients), access to credit, or subsidies for the purchase of equipment (Ngongi, 2018; Ozor et al., 2018). Without such efforts, CEA could exacerbate social injustice by excluding the very people who stand to gain the most from it.

Contributions from the case studies

All forms of CEA were regarded as having potential to provide viable livelihoods, across all the study areas, especially in the context of a lack of jobs for young people, poor remuneration for workers in other sectors, and marginal conventional farmers' struggle with poor yields, high costs, and fluctuating prices.

The study found that CEA can provide opportunities to escape poverty through employment, whether by operators directly, through development of an outgrower network, or by prompting supply chain development that leads to even more employment and, possibly, less exclusive entrepreneurship opportunities.

The findings on entrepreneurs, however, contrast with those in the above literature review, since starting up in CEA depends on access to start-up funds or finance and a small parcel of land or premises (see Table 3 for example start-up costs), as well as a certain level of education (see section 3.4 on barriers). Many of the founders of the case studies have advanced degrees (some from US or European universities) and previously had lucrative careers in fields including IT (Letcetra Agrictech, Indica), pharmaceuticals (Aqua Farms, India), financial services (GreeOx, Vietnam), epidemiology (Fresh Direct, Nigeria), electrical engineering (Save Our Agriculture). As such, CEA entrepreneurship is not a route out of poverty, but rather a means of self-employment or easier, more lucrative farm-based livelihood for people with means. For the same reasons CEA is currently of limited effectiveness as a mechanism for advancing social equity in the study areas, the research showed efforts by early adopters to make CEA more accessible to individuals with little means or who face discrimination (e.g. by offering free training or developing outgrower opportunities), in keeping with the requirement identified from the literature review.

While the literature review on social equity did not yield any information relating to gender equity through the practice of CEA (beyond targeted NGO efforts), the case studies showed that accessibility of CEA to prospective female farmers differs between the study contexts. Some interviewees deliberately create opportunities for women in CEA, either as a route to empowerment in male-dominated society or to off-set societal barriers to their participation.

There was also some evidence to support benefits of CEA for displaced people and refugees, but this was seen as is contingent on international organizations providing equipment and contracting local experts or NGOs to guide them.

The following paragraphs provide more detail on the interviewees' insights related to poverty reduction and social equity.

Entrepreneurship

Growers in Kenya, Nigeria and India who provide training in hydroponics or aquaponics identified four common categories of people who are interested in starting commercial CEA ventures: young people looking to start their own business; conventional farmers wanting to try a new approach or boost insufficient income; people in other professions seeking additional income; and white-collar workers who are close to retirement.

Young people: CEA can help address the problem of lack of jobs for youth, although it is not a viable option for all young people, at least until they have accumulated a minimum of experience and access to finance. Prospective entrepreneurs are typically well-educated (graduates with an aptitude for technology) and the high start-up costs (see Table 3 for examples) mean only those who have sponsorship from their families are likely to establish a hydroponic/aquaponic farm after their training. For example, the founders of Herbivore Farms in India were sponsored to set up their farm in a disused warehouse by their parents.

Farmers: CEA can significantly boost farm incomes for those who are struggling or disillusioned with conventional methods, if they can secure finance to cover start-up costs. In India for instance, marginal farmers typically have just one or two acres to farm due to the repeated division of land between children over generations, from which they generate insufficient annual income of around US$1,000 through conventional farming. Through hydroponics or aquaponics, farmers can grow higher volumes of vegetables on a small plot; the risk of crop-loss through soil-borne diseases is eliminated, and enclosed structures provide (varying degrees of protection) against insects. In Sri Lanka, the three polytunnel hydroponic growers concurred that hydroponic growers had higher and/or more stable incomes, although the small scale of hydroponic farming at present means the farm- or family-level gains are not reflected in the poverty level or economy of the area.

As for BSF, the majority of farmers in Kenya and India who are interested in rearing larvae wish to have a cheap, consistently high quality, protein source for poultry or pigs. In India, the fluctuating cost of soybean meal is a motivating factor for chicken farmers; whereas in Kenya using BSF larvae as feed bring operational benefits: the chickens are healthier and produce higher quality eggs, while pigs are ready for market sooner. The start-up costs for small-scale BSF exploitation can be lower than for other forms of CEA, depending on the size and chosen set-up, making it accessible to people of lower means as well as those with resources.

Workers in other professions: Hydroponic/aquaponic production presents workers in other professions with a means to supplement insufficient income. People in formal employment are in a better position to obtain start-up loans than those who are currently unemployed.

‘Some people are employed but their job is not meeting their needs. They found an opportunity in hydroponics because they can go to work in the morning and tend to their farm in the evening, and doing that they are making some extra income.’ (Debo Onafowora, BIC Farm Concepts, Nigeria.)

An example is Hope Wanjiru in Kenya, a former hairdresser who took up CEA after having children, as her previous earnings were insufficient. To do so, she had to take out a loan.

All 10 members of Greenthumbs CBO in Kenya have other jobs; among them an accountant, a plumber, a pharmacist, and individuals who work in insurance and in fashion and beauty. The members make some additional money out of the venture but their main motivation is ‘to do their part in making the world a better place for the youth and the vulnerable populations through agricultural and other social entrepreneurship projects’.

Older white-collar workers: Hydroponics/aquaponics growing is a physically undemanding occupation that they will be able to continue into retirement. For instance, one of the polytunnel growers in Sri Lanka began his polytunnel farm at the age of 50 whilst working as a schoolteacher. This group typically has some capital to cover start-up costs.

Employment opportunities

Aside from providing opportunities for individual entrepreneurs, some CEA operations may contribute to poverty reduction through employment opportunities. This is more applicable to larger and more technologically advanced operations: the consensus among the Sri Lankan polytunnel operators is that one person can run a polytunnel of up to 4000 sq foot ($372m^2$) without a workforce, although one brings on a casual laborer to help at the potting stage.

Honest Greens currently has 14 employees, and The Lanka Salad Company around 30. Both employ staff from the local area. A representative of The Lanka Salad Company cited an unemployment rate of 8% in Sri Lanka, with 4% of the population living below the poverty line and some geographical pockets of extreme poverty. She said:

‘We are in a rural environment so we can employ local rural communities that are typically a bit more susceptible to poverty and lack of employment.’

In BSF farming, Sagel Oik Ventures in Kenya employs 11 people who produce 220 to 250 kg of live larva per day, while the BSF unit established by Exocycle at the poultry operator in Tamil Nadu, India will employ 5 laborers.

All employers said that they provide decent jobs, with competitive salaries and in good conditions. The Lanka Salad Company in particular emphasized the importance of employee development.

Outgrower network

Another way in which CEA may contribute to poverty reduction is in creation of an outgrower network, whereby an established operator instructs others in their practices and contracts them to grow produce to supplement their own capacity. This model, which is already run by CRAFT Compounds (India) under its Rural IDEA model, provides a guaranteed market to growers who may otherwise not risk starting a hydroponic or aquaponic venture. Given that it can provide a market, CRAFT Compounds is in discussion with banks over tri-partite loan arrangements for prospective out-growers who would not otherwise qualify for finance.

By contrast, the 'plug and play' franchise model envisaged by Honest Greens is 'not a poverty reduction scheme for agricultural entrepreneurs', since the franchise-holders must have substantial capital to adapt or construct a building and fit it out with technology.

Supply chain development

Lastly, supply chain development can contribute to poverty reduction by creating economic opportunities in associated industries. Development of the hydroponics supply chain is underway in Africa, as two interviewees run companies providing hydroponic equipment and inputs, alongside their own farms and training operations.

In Kenya, a recently established BSF trade association (80 members currently) is actively working to build a value chain, with the objective of developing specialized roles at different nodes. For example, there is a need for people to aggregate BSF larvae so that small scale producers can access large markets that require quantities beyond the capacity of any one individual. New niche industries are also emerging to support BSF farmers. One such niche is the provision of nets for adult fly cages; another is the fabrication of reusable wooden strips for egg-laying.

In Ghana, documents relating to Ento-prise contained evidence of interest from stakeholders in participating in developing BSF production supply chain. However, it is unclear whether this will come to pass as Ento-prise's facility was only a pilot and was not deemed to be commercially viable due to insufficient waste volumes (despite its location at a market).

In the case of large scale Kenyan BSF operator, Sanergy, it is the input side of the operation – the collection of human waste from installation of latrines in slums – that creates livelihood opportunities through a franchise model.

Table 3: Set-up costs of case study CEA operations, where available

Operator	Country	Structure and system	Cost (USD)
The Lanka Salad Company	Sri Lanka	400m^2 greenhouses, steel framed with plastic Hydroponics (NFT); pan and fan evaporative cooling.	c.$40,000 for initial units ($100/m^2); c. $20,000 for subsequent units ($50/m^2) once infrastructure established
P.K. Samarasinghe	Sri Lanka	92m^2 polytunnel, UV polythene and net walls Hydroponics (unspecified method)	$2,500-3,000 (2017 prices)
S. Ranasinghe	Sri Lanka	186m^2 polytunnel, polythene roof and side walls of nylon/fabric net. Hydroponics (drip system)	c. $5,000 (estimated 2021 prices)
K. Chaminda Rangana	Sri Lanka	92m^2 polytunnel Hydroponics (drip system)	c. $3,500 (2012 prices)
Hydroponics Africa	Kenya	130m^2 vertical A-frame structure for hydroponics (drip system), not including greenhouse; includes	$2,000

Operator	Country	Structure and system	Cost (USD)
		seedlings and nutrients for 12 months	
Greenthumbs CBO	Kenya	Greenhouse structure Aquaponic system (solar pump); raised beds of timber and down-liners	Unable to provide; aim at cheap replication by local farmers
BIC Farm Concepts	Nigeria	240m^2 polytunnel, includes structure, covering, substrate, troughs, irrigation system, seeds, nutrients	c. $10,000
Soilless Farm Lab	Nigeria	180m^2 greenhouse Hydroponics (ebb and flow or Kratky); costs variable depending on number of layers, crops, special requirements; seek local materials to keep costs low	c. $2,000
CRAFT	India	200m^2 greenhouse Aquaponics (raft system); gravel medium	c. $16,100; aiming to bring down to c.$10,750
Sagel Oik Ventures	Kenya	Greenhouse, purpose built with concrete base, plastic roof and net walls BSF farming using plastic crates for larvae; adult fly cages of 1m^3 using greenhouse netting	Main cost is greenhouse; unable to provide figure
Exocycle	India	Re-purposed chicken shed; investment in 3000 trays; fabrication of fly cages and breeding room	 $12,000 $3,000

Socio-economic status

Among almost all the interviewees there is a common ambition to make CEA more accessible to people from less well-off socio-economic backgrounds, with various practical efforts already being implemented. For instance:

- Several of the interviewees offer training for free, either as a matter of course or (where their business model depends on fees) periodically for those of little means.
- Hydroponics Africa (Kenya) has a range of commercial hydroponic system available to be as accessible as possible to those who can only afford to start small (although the interviewee admitted that even these are too expensive for many people);
- CRAFT Compounds (India) is directing its technical research towards reducing start-up costs for marginal farmers.
- Both Peter Chege of Hydroponics Africa (Kenya) and CRAFT's Vijay Yelmalle (India) are actively discussing with banks over ways to assure a market for new growers, so that lenders are more willing to offer finance.

- An initiative at Kabete Rehabilitation School in Kenya aims to train adolescents from deprived backgrounds to start their own hydroponic farms. Extension services are provided by Miramar International College, with training (in the entire value chain, not just growing) funded by GIZ and greenhouse set up costs funded by KCB Foundation.
- The Lanka Salad Company's (Sri Lanka) nascent out-grower network began as a corporate social responsibility initiative to improve the productivity of poor women farmers in rural areas and provide them with a route to market.

Education level

Currently it is mostly educated people with good IT skills who hear about hydroponics and aquaponics and have access to the internet to search for information. As noted above, several of the founders of case study operations have advanced level degrees, some from international universities. However, there are expectations that it will catch on and proliferate more widely over time.

'The copying culture in Nigeria is going to drive hydroponics. Most people that are doing something about it is because someone else did something, or they heard about it from someone. So currently it is still at the starting stage, but I think it will grow fast.' (Debo Onafowora, BIC Farm Concepts, Nigeria.)

In Sri Lanka, one of the individual polytunnel growers said they were inspired to take up hydroponics after observing a neighbor's success.

A major motivation of Greenthumbs CBO (Kenya) was to 'develop an approach that other local farmers can copy and use'. This underscored the team's choice of structure, parameters and growing medium, all of which had to be as affordable and locally accessible as possible.

Gender

The accessibility of CEA to prospective female farmers differs between the study areas.

In India, CRAFT Compounds reported receiving an equal number of training enquiries from urban men and women. In rural areas it is usually the man who makes the first contact, but couples tend to participate in training together and work alongside each other as growers. This is broadly in keeping with family farming practices in the country:

'There is no gender gap when it comes to farming. It's not particularly a man's domain, which predominantly happens in the rest of the sectors. Here it is more like families working together towards tilling the land.' (CRAFT Compounds, India.)

In Kenya, Peter Chege (Hydroponics Africa) reported more women than men attending hydroponics training sessions in the first instance, but they often bring men to visit his farm later. He has noticed that women are often more interested in a small unit at the household level, whereas men tend to have their eye on commercial opportunities. Consequently, access to opportunities in hydroponics by Kenyan women may not support equitable livelihoods so much as household level food security.

Rosanne Mwengi (Sagel Oik Ventures, Kenya), who offers training in BSF both locally and online to people in all locations, reported slightly more enquiries about BSF training from men than from women. Like Chege, she suggested this could be explained by men's commercial ambitions:

‘I think it is because of the scale of operations… The majority want to take advantage of the fact that it is a new space, and they can get in and cut their niche in their various countries.’ (Rosanne Mwengi, Sagel Oik Ventures, Kenya.)

As for Greenthumbs CBO (Kenya), it was deliberately set up to have more women members than men, partly to enable young women to earn extra income and partly to empower them to take decisions, in a context where bread-winner tend to be older and male.

In Nigeria, Debo Onafowora (BIC Farm Concepts) reported the male:female ratio at training courses is 60:40. He saw this as positive because women make up only 20% of conventional farmers in the country, and said hydroponic farming ‘is more attractive [to women than conventional farming] as it is physically easier and more dignified’. That said, women may not always make the decision to take up hydroponics themselves; sometimes male heads of household attend training with a view to setting up a CEA unit for their wife to run.

Samson Ogbole (Soilless Farm Lab, Nigeria) reported a similar male-female ratio among training course applicants, he deliberately selects more women than men. This is partly to compensate for the acknowledged cultural and practical barriers to women attending training on CEA techniques (see next section on ‘barriers’).

In Sri Lanka there are significantly more male small-scale hydroponic growers than women. The three sole polytunnel growers all attributed this to women being more risk-averse and the barriers they face in obtaining finance (see section on ‘barriers’). A provincial subsidy scheme aims to encourage and facilitate female hydroponic farmers, subsidizing 60% of start-up costs for women and 50% for men.

Internally-displaced people and refugees

Some programs have also made hydroponic growing accessible to internally displaced people and refugees. For instance, displaced people in Northern Darfur have been re-settled on land in areas with harsh climatic conditions, including extreme heat. Their inability to grow vegetables has implications for nutritional status.

Peter Chege (Hydroponics Africa, Kenya) was commissioned by an NGO to study the feasibility of installing hydroponic systems. On the technical side, he showed it is possible to reduce the heat inside structures by using double-layered shade net. On the cultural side, the installation of a community unit in which each family has their own area worked better than individual household units, because people go on a daily basis for the social contact, compete with each other, and learn from each other’s questions.

In refugee camps, where space is limited, wall-mounted systems with minimal labor requirements are most suitable.

While these lessons are helpful, making hydroponics accessible to displaced people and refugee populations depends on NGOs to fund both structural hardware and consultancy by local experts.

Resource use and natural environment

Contributions identified in the literature

Sustainable Agricultural Intensification (SAI) has sustainable use of natural resources at its core. This is claimed to be particular strength of CEA due to recycling of water and minimal land, fuel, energy and emissions footprints. Some scientific studies have sought to test these claims.

One of the least controversial resource-related claims is that CEA requires significantly less **water** than open-field agriculture. In her review, Hughes (2018) was convinced by evidence that CEA can require up to 90% less water than open field agriculture, as water is recycled within the system rather than being lost via transpiration. Moreover, because the water is recycled, there is less release of plant nutrients as pollutants in freshwater systems (See Box 2 on the Kenyan flower industry).

There is also little or no need to use **pesticides** or insecticides in some CEA systems, though vulnerability to pests, disease, and weeds depend on whether the system is partially or completely closed. This further reduces pollutant run-off, as well as contribution to the demise of insect pollinators (Mytton-Mills, 2018; Benke and Tomkins, 2017).

Another area of general agreement is the requirement for less **land**, as CEA systems can deliver between 4 and 20 times more produce on the same productive acreage (HOH, 2019; Avgoustakis and Xydis, 2020). Soilless forms of CEA can also be installed on degraded or contaminated land. In theory this would allow farmers to rotate remaining soil-grown crops more efficiently and leave plots fallow for the soil to re-gain condition (Hawkins-Row, 2018). Despommier (2019) suggests that it might also enable re-wilding and return to hardwood forests and projects that the restoration of 60-70% of forests (two trillion trees) could sequester enough carbon to reverse the rate of global warming. However, as discussed in section 3.3.1 above, CEA is expected to remain a smaller, complementary sector to open field production; for instance, the commitment of all available roof area in London, UK, to containerized agriculture could provide 6% of the city's fruit and vegetable needs (Rodriguez, 2009). For broadacre crops like rice and wheat, the main benefits are likely to be in speeding up breeding programs. As such, there is unlikely to be such a shift of broadacre production to CEA as to free up significant quantities of land. Rather, it will play a role in restricting the expansion of cultivated land to feed growing urban populations, thereby preserving natural resources, ecosystem services, and recreational areas.

Some authors have asserted that CEA enables a reduction in **fossil fuels**, partly because tractors are redundant and partly because produce is not transported across long distances in refrigerated trucks, since it is grown close to the place of consumption (Avgoustakis and Xydis, 2020; Benke and Tomkins, 2018; Hughes, 2018; HOH, 2019). No robust, publicly-available data were identified to substantiate the claim, however, and Goodman and Minner (2019) point out that fuel usage varies by vehicle type. Moreover, in some cases inputs or construction materials may be transported over long distances even if produce is not (Nwosisi and Nandwani, 2018). The same caveats apply to claims that CEA can improve the environment through reduced **greenhouse gas emissions** from long-distance travel.

The question of **energy use** is the most complex. Some academic studies have compared usage between individual crops in CEA versus open-field systems (or traditional greenhouses which rely on sunlight and can be ventilated by opening roof panels vs vertical farms that require artificial light and cooling) in the same or different global locations (e.g. Graamans et al., 2019; Barbosa et al., 2015; Pons et al., 2015). Such comparative studies are helpful insofar as they signal which systems may be more advantageous, under what conditions, for the crops in question.

From their review of vertical farming in New York, Goodman and Minners (2019) found the approach makes sense from an energy perspective in settings where artificial heat and light sources are not required, but when these parameters require external energy, the environmental advantages drop away. Similarly, Armanda et al. (2019) concluded that IUA (including forms of CEA) is likely require more resources, infrastructure and energy than either traditional urban agriculture or rooftop agriculture. They recommended testing this hypothesis with an environmental life cycle assessment for each technology type and in each proposed location – especially in low-income countries, where population growth is increasing most rapidly. Benis and Ferrao (2018) also concluded that the high energy intensity of CEA in cities means it is not inherently more sustainable than traditional, open-field agriculture, and is highly context dependent. More, rigorous research might eventually inform holistic (environmental, social and economic) decision support- and modelling tools to be applied for each proposed initiative, in each setting (Iddio et al., 2020).

While the short answer to whether CEA uses less energy than conventional production is, 'it depends', some useful work has looked at how energy use might be reduced or better managed.

One way in which energy efficiency can be improved is through passive conditioning – that is, building energy efficiency into the design of a structure through ventilation, insulation, evaporative cooling (Benis and Ferrão, 2018). Another is to improve efficiency through intelligent operation, including using smart sensors and monitoring systems (Iddio et al., 2020). Thirdly, new and improved components are coming to market, such as light-emitting diodes (LEDs) that produce less heat than lumen-producing filament grow lights (reducing the need for ventilation). The cost of LEDs has significantly reduced in the last decade (Mytton-Mills, 2018; Bantis et al., 2018). Other technical advances include air-source and ground-source heating, and photovoltaic glass.

Where energy needs cannot be reduced (any further), it might be possible to reduce environmental impact by using only renewable energy – although it appears that renewable energy is not de facto better for the environment. Hughes (2018) cited findings from Wageningen University that the only sustainable energy sources for vertical farming are water, wind and nuclear, all of which have a carbon footprint of under 25g/KHW CO2; while Al-Chalabi's (2015) energy modelling of Despommier's (2009) vertical farm plans found that the structure would have insufficient surface area for solar panels to exclusively meet to its energy needs. Another approach is circularity – or coupling the energy needs of a CEA facility with outflows of a host building or co-located system – which can meet high energy needs by re-claiming energy that would otherwise be wasted (Benis and Ferrão, 2018; Styles and Wootton-Beard, 2017). Potential co-located systems include anaerobic digestion, renewable energy production, CHP Plants, server farms, industrial food processing plants.

Finally, there is evidence that certain CEA systems can contribute the **waste reduction**. Jonathan Lodge, Founder and CEO of UK technology company City Farm Systems Ltd (Lodge, 2019), drew attention to the utility of sensors – even low-cost forms – for monitoring and altering growing conditions to modulate supply to meet fluctuating demand, thereby reducing waste caused by over-production. BSF farming, meanwhile, is acknowledged as a sanitary form of waste management that diverts organic matter away from landfill sites. The use of BSF larvae as animal feed is also more sustainable than soybean meal and fishmeal, which are often products of industries that contribute to deforestation and depletion of fish stocks respectively (Joly and Nikiema 2019). Lodge (2019) also highlights how use of low-cost sensors can help reduce waste, as they can be used to monitor, and then adjust, growing conditions to modulate supply to meet fluctuating demand.

While the above literature review points to some benefits around resource use and natural environments from certain forms of CEA, Hughes (2018) points out that there is a lack of publicly available data from CEA enterprises. This raises questions about whether there is enough evidence yet to support their optimistic outlook. Armanda et al. (2019) highlight the need to take on board the lessons of the Green Revolution and ensuring long-term sustainability for 'people, planet, and profit', especially in developing countries. To this end, they advocate comprehensive life cycle analyses for all deployment of IUA, including CEA technologies.

Contributions identified from the case studies

As discussed in section 3.3 above, the forms of CEA practiced in many of the case studies were selected for their viability and expediency in respect of climate- and resource-related constraints, with a notable preference for natural light wherever possible.

Similarly, the majority opted for water-efficient technologies that enable them to maintain production despite fluctuations in rainfall throughout the year, and made no mention of need to preserve water table levels.

One resource-related challenge in which CEA technologies were seen to ameliorate is land use.

In term of protecting the natural environment, reduced or zero pesticide use, reduced carbon emissions, and waste reduction were three areas that support and add to the findings from the literature review.

The following paragraphs provide more detail on the interviewees' insights in these areas.

Energy

All of the greenhouse-based CEA operations make use of natural sunlight, generally use passive conditioning methods due to the high cost and/or unreliability of artificial sources, and made no claims about contributing to environmental sustainability.

The indoor operations identified tend to use LED lighting, including Fresh Direct (Nigeria), GreeOx (Vietnam), and Herbivore Farms (India). Honest Greens in Sri Lanka also relies on artificial energy but strives to make its operations as sustainable as possible. To this end, an interviewee said energy is 'a big problem', but the company is investigating installation of solar panels to offset some of the carbon costs.

Land issues

Growers (both hydroponic and aquaponic) in Nigeria, Kenya and Sri Lanka all cited land pressures as a local challenge that hydroponic or aquaponic production systems can ameliorate.

According to The Lanka Salad Company, Sri Lanka has 2.3 million hectares of agricultural land, of which 1.3 million hectares are occupied by smallholder farms of two hectares or less. This fragmentation limits the quantities farmers can grow and may lead to soil degradation. Hydroponic systems enable more produce to be grown on less land (only the land on which greenhouses are located) and, since soil is not used, prevents degradation.

In Nigeria both Samson Ogbole (Soilless Farm Lab) and Debo Onafowora (BIC Farm Concepts) mentioned land use pressures as a result of rapid urbanization. With the disappearance of traditional grazing lands, nomadic herdsman increasingly encroach on, and damage, farmlands. The result is, frequently, violent conflict. Both of them grow (or have previously grown) fodder (grass) hydroponically. Onafowora proposes establishing hydroponic 'fodder centers' that could feed herds using just 1% of the land, particularly close to major cities like Lagos, where 7,000 head of cattle are slaughtered each day.

Pesticide application
Growers in Sri Lanka and India cited reduced (or non-existent) use of pesticides among the environmental advantages of CEA. One of the small-scale hydroponic vegetable growers in Sri Lanka said he uses less pesticides than in an outdoor farm – only two or three times in a growing cycle if crops are affected by fungus due to high humidity. CRAFT Compounds (India) considers zero pesticide use as a key advantage of aquaponics over hydroponics:

'We are not supposed to use chemical pesticides [in hydroponics], and if we do, we are supposed to do it responsibly. But nobody can guarantee that, people may be doing it to earn money. So, in that way aquaponics is very very promising because it is evidently intolerant to chemical pesticides. I know if the farmer is growing aquaponic vegetables I am 100% sure he not using chemical pesticides because he does not want to kill his fish.' (CRAFT Compounds, India).

Similarly, the absence of pests in completely enclosed systems, such as the repurposed warehouse of Herbivore Farms in India, means there is no need for pesticides. This is leveraged as a significant attribute in company marketing.

Carbon emissions
Interviewees in Kenya and Nigeria remarked on long distance transportation of conventionally-grown vegetables, from place of production to market, resulting in reduced carbon emissions. Since hydroponics enable vegetables to be grown closer to markets regardless of local soil conditions, they claimed the technique contributes to reduced emissions.

Waste reduction
Some growers also cited waste reduction as a benefit of growing sensitive produce close to market.

Debo Onafowora (BIC Farm Concepts, Nigeria) also highlighted the huge volumes of food loss and waste as a result of transportation of tomatoes within Nigeria, with 50% of the tomatoes grown rotting during their journey. Similarly, the general lack of cold chain in Sri Lanka leads to 40% post-harvest food losses in Sri Lanka, according to The Lanka Salad Company (which engages specialist private cold chain partners to transport its lettuce the short distances to market):

'As soon as we cut that root, there is little more perishable crop than lettuce… getting it from A to B in reasonable condition is not to be over-estimated.' (Charlie Hancock, The Lanka Salad Company, Sri Lanka.)

In the case of Fresh Direct in Nigeria, an earlier endeavor to produce vegetables in a greenhouse in a rural area was abandoned due to food losses, as transportation to urban markets was disrupted by fuel shortages and there was no cold storage available. Growing in shopping containers closer to urban markets is considered advantageous for reducing food loss and waste.

Waste reduction is also a clear benefit of black soldier fly farming. In Kenya, local government policy requires that waste be collected and taken to a dump site, but organic matter (which makes up the largest component) is not generally separated out before it enters landfill.

‘The greatest benefits we are gaining from black soldier fly farming is its conversion of waste into value, that I cannot over-emphasize. Then the many big heaps of waste that you probably will find are being turned into beneficial products.’ (Rosanne Mwangi, Sagel Oik Ventures, Kenya.)

In India, poor waste management is a problem at the individual level, with many people putting their household waste in bags and dumping it in the road or on someone else’s property. Better waste management is a primary objective of Exocycle (India), which is in talks with local government for trucks that collect organic roadside waste to bring it straight to the BSF facility.

In addition to helping waste management at the municipal level, BSF farming can eliminate farm waste or by-products, and address sanitation issues. Rosanne Mwangi feeds her BSF larvae a combination of organic waste and pig feces from her farm; while the BSF facility set up by Exocycle at the chicken plant in Tamil Nadu will mix dead chickens (rendered and chopped) from the hatchery. Exocycle is also in contact with a government officer with the Pollution Control Board in the coastal city of Alleppey in Kerala state, who would like to investigate BSF faming to manage waste from the shrimp-peeling industry. The pilot BSF facility constructed as part of the FORWARD research project in Indonesia is located at the wholesale market to facilitate access to waste streams.

As for Sanergy, a large-scale BSF production facility in Kenya that has attracted significant international investment, the majority of publicity and media messages emphasis first and foremost the provision of a sanitary solution for human waste in urban slums. The business model involves setting up and franchising latrines in the slums, then collecting the waste for treatment and processing by BSF into compost and protein for feed.

BOX 2 | The Kenyan flower industry, a case for comparison

The Kenyan flower industry provides a useful case of comparison with CEA for food crops and animal feed. In 2015, the sector yielded 122,825 tonnes of cut flowers for export, with a value of KSh 62.9 billion (US$ 5.6 million). The sector has grown exponentially since the 1980s, and now employs over half a million people (Kenya, n.d.).

Although the flower industry is a significant provider of livelihoods, there have been reports of low pay, poor environmental conditions, massive use of natural resources, and pollution from greenhouse operations, albeit based on data from over a decade ago (Leipold and Morgante, 2012). When magnified to large scale operations and the industry as a whole, these issues can have a significant impact on sustainable development.

Efforts have been made to address the labour issues, not least due to demand for corporate social responsibility and Fairtrade certification by European consumers (Leipold and Morgante, 2012).

Most flowers in Kenya are grown in soil, and the sector is characterised by use of modern and precision techniques including drip irrigation, fertigation systems, greenhouse ventilation systems, net shading, fertilizer recycling systems to prevent wastage, artificial lighting. There are projects to introduce hydroponics, such as a consortium of Dutch greenhouse builders, researchers from Wageningen Plant Research, and Kenyan farmers, to establish a 16,000 m^2 demonstration project in Kenya to reduce water use and run-off (Elings, 2013)

The Kenya Flower Council, established in 1996, is a voluntary association for growers and exporters of all sizes, that works towards safe, responsible flower production, workers' welfare, and environmental stewardship. One of the key roles of the Council is to liaise with governments, development agencies, media, trade bodies and unions, non-governmental organisations, and other stakeholders, to create an enabling environment for the sector. Also, the Council runs its own certification scheme, that is guided by an Accredited Quality System Regulations that defines the management, auditing and certification process (Kenya, n.d.).

According to the Kenyan government, the industry attracts investors due to 'solid infrastructure, favourable climate, global-positioning of Kenya and a productive workforce' (Kenya, n.d.).

Conclusion on viable CEA technologies and conditions

The primary purpose of the study was to identify which CEA technologies merit investment, and under which conditions, to advance SAI in Africa and Asia.

To do this, a study was conducted on the current practice and future potential of CEA in low- and lower-middle income country contexts. The first two questions addressed in the study were:

1) Which CEA technologies are most likely to be viable in low- and lower-middle income countries in Asia and Africa, in terms of making use of locally-available human, capital and natural resources and production efficiency?
2) In what ways can CEA contribute to the sustainable development objectives of SAI in low- and lower-middle income contexts?

CEA technologies that are most likely to be viable

The findings support the principle that the type, systems and control parameters in CEA must be tailored to local contexts. Generally speaking, however, greenhouses and polytunnels were found to be most viable in all the study contexts, in particular those with structural features that harnessed local energy and so that they did not depend on artificial energy and with vents or shade nets for temperature control. In comparison to indoor systems with completely controlled environments (in purpose-built or re-purposed buildings or other enclosed spaces like shipping containers, greenhouses were more vulnerable to climate events and pests, but these risks were mitigated by the lower costs of construction and repair using local labor. Moreover, the enterprises could be easily scaled up by adding more relatively inexpensive greenhouses.

There was some secondary evidence that shipping containers and re-purposed buildings can house viable CEA operations, partly because they have enabled entrepreneurs to set up in built-up urban locations where there is no space for greenhouses. The higher operating costs compared to greenhouses, due to the need for LED lighting and air conditioning, are off-set by reduced fuel costs to transport produce to market. Furthermore, the risk of losing crops due to occasional electricity outages was deemed less than the risk of losing crops in transport from rural areas to urban markets due to fuel shortages or absence of adequate cold storage. Another reason why completely enclosed structures were considered viable is that parameters can be set to provide optimum conditions year-round, enabling the higher running costs to be off-set by higher, consistent yields.

Although it was not possible to directly compare set-up costs of farms in shipping containers and re-purposed buildings to set-up in purpose-built structures, logic has it that the former are cheaper as there are only adaptation and fit-out costs, no construction costs.

Hydroponic systems were most viable for vegetable production, including in inhospitable-drylands due to their minimal water use. In most contexts cheap, locally-available materials were available for use as substrates. Where electricity was expensive and/or irregular systems, that do not need pumps to lift or spray water on to the roots, such as the gravity driven Kratky or ebb and flow technologies, were preferred.

Where there is sufficient water and reliable electricity, aquaponics was found to be a viable form because it has two outputs – vegetables and fish – which provide complementary sources of nutrition and income.

In both hydroponics and aquaponics, vertical, pyramid or A-frame structures were popular because they provide greater growing area than monolayer beds while still enabling use of natural sunlight.

The study found increasing interest in Black Solider Fly (BSF) farming for the production of animal feed and compost, due to the potential for low start-up costs and low running costs, as there is little requirement for artificial energy costs. That said, commercial viability is dependent on access to sufficient quantities of waste, which was a major ongoing preoccupation for all BSF farmers. It is unlikely to appeal to the same entrepreneurs as hydroponics and aquaponics because the outputs are animal feed and compost, rather than food for human consumption.

There was very little evidence of use of AI sensing technology, which was mentioned only in documentation relating to one case study and, in another instance, in the context of a farmer's belief that it would be very helpful, if it could be accessed.

The above account is a good indicator of which CEA technologies are most likely to be viable in low- and lower-middle income African and Asian countries. However, consideration of the more specific findings must be qualified by acknowledging some limitations of the study. Conducting the study remotely meant that it only involved operations that had some internet presence; lack of response from people practicing some forms of CEA (notably in repurposed buildings, shipping containers) meant that some specific issues faced by those working in completely enclosed systems could not be fully captured. Moreover, it was not possible to fully explore the use of AI sensors to monitor operating conditions. The inability to observe practices in person means, which meant that some technical aspects may be under reported. Another shortcoming is that it is very difficult to make direct comparisons over yield and revenue between operators who are cultivating different crops in very different economic contexts. Finally, interviewees with a mission to build CEA within their countries or regions, such as through providing training, were more willing to share technical and commercial information than those operating in hi-tech, commercial and competitive settings.

Contribution of CEA to sustainable development objectives of SAI

The study found that CEA producers could contribute to aspects of food and nutrition security through improved food quality and nutritional value, and promoting affordability by reducing price fluctuations. The question of affordability is complicated by the pursuit of high-end, niche markets by some operators, to off-set high start-up and running costs. CEA is nevertheless expected to make a greater contribution to access and availability aspects of food security in the face of climate change and depleted numbers of conventional farmers.

Due to the technical expertise and capital required, CEA business ownership will not be a route out of poverty for poor and marginalized people but, as it expands, it could create clean and less arduous employment opportunities. Moreover, as more people work in CEA enterprises more will acquire the knowledge and expertise needed to branch out on their own ventures. It will also create opportunities in value chains from input supply through processing to final point of sale. Due to the light nature of the work and the ability to be situated close to where potential workers live, CEA has the potential to advance social equity for women, youths and disadvantaged groups. However, that will require deliberate some proactive action to remove some entry barriers such as by allowing flexible hours to accommodate domestic responsibilities, providing childcare facilities or ensuring access for disabled workers

The main resource-related benefits of CEA identified in the study contexts were its inherent land-use and water use efficiency. Other benefits for the environment included zero pesticide use, reduced carbon emissions due to being sited close to markets, and reduced waste in the short supply chains. BSF production had the virtue of turning organic waste into useful products. Indeed, for one large scale BSF operation sanitary waste processing was the primary communications message, with the production of animal feed and compost secondary. While high energy use was acknowledged as a sustainability 'problem' by one indoor farm, there is a belief that some of the carbon impact may be off-set through solar panels.

Conclusions on types that represent investment opportunities

The overall conclusion drawn from the first two study questions was that, with the right technologies, CEA enterprises can be viable and can make some positive contributions to food security and nutrition, poverty reduction and social equity, and resource use and the natural environment. It follows that the emerging CEA sub-sector merits further investment to realize its potential to make a more significant contribution to achieving the objectives of the Sustainable Agricultural Intensification (SAI) initiative in Africa and Asia. CEA systems that are worthy of investment in these contexts include:

- Hydroponics, and aquaponics, and BSF farming practiced in greenhouses and polytunnels that can be constructed cheaply using locally-available materials yet having the structural features required for controlling the growing environment.
- Hydroponics, aquaponics and BSF farming practiced in re-purposed buildings and other spaces in urban areas (including those that make use of readily available materials such as disused shipping containers), insofar as their location close to the point of sale of produce and the ability to grow consistent, high yields all year round provide significant benefits that off-set higher energy use.
- Hydroponics and aquaponics with water and nutrient delivery techniques that require as little artificial energy as possible. Systems with higher energy requirements will only be viable with higher productivity and/or markets willing to pay higher produce prices.
- CEA operations of all kind that use predominantly low carbon sources of artificial energy, such as hydraulics, solar and wind energy – on the proviso that environmental costs of sourcing and installing materials do not negate the operating benefits, and the financial costs of set-up do not need to be off-set by selling vegetables to high-end, niche markets rather than local markets.
- Hydroponic and aquaponic systems built with multi layers, vertically or on A-frames, that increase the number of plants per unit land surface while still able to rely on sunlight.
- CEA systems with dual outputs that make them more financially robust, such as aquaponics producing fish and vegetables, and BSF farming producing animal feed and compost.
- Systems that make use of reliable, constant local sources of inputs particularly those that utilize the waste from other industries, such as BSF production which can use manure and organic municipal waste. This includes CEA operations that are co-located with industries whose bi-products or waste are used as inputs.
- Small to medium scale enterprises which can be established by smallholder farmers and young entrepreneurs, and especially those that, with incremental investment, can be readily scaled up using the same basic infrastructure or developed in franchising or out-grower schemes to improve the economic prospects of marginal farmers.
- CEA operations that use (or are willing and able to use, if granted access) AI sensors to monitor, and then adjust, growing conditions, enabling them to rapidly scale up and scale down production in response to fluctuating demand.
- CEA operations that can tap markets for traditional and locally consumed vegetable varieties, with the CEA asset of being able to offer produce year-round at constant prices. These are more likely to be financially sustainable that those that produce exotic vegetables for niche markets.
- CEA enterprises that are operating close to the points of sale for their produce which have the advantage of reduced handling and transportation losses and disruption by climatic events. These include CEA businesses in urban and peri-urban areas where pressure for land and the consequent cost of land make restrict open field agriculture or where there is a risk of soil and/or water contamination.

- CEA operations in areas where residents have limited access to nutritious food, and where environmental conditions are unsuitable for most food-growing, such as in settlements for displaced people in arid areas.
- CEA operations that are clustered within a locality, which increases the likelihood of stimulate other local economic opportunities by catalyzing incentivizing businesses along whole value chains from input production and supply to points of sale to consumers. In addition, such concentrations of CEA operations enable growers to benefit from shared infrastructure; joint training; more efficient extension services; sharing of lessons learnt and expertise; collective negotiating power over inputs and market access; collective lobbying for enabling policies; and reduced overheads for investors and lenders.

Enablers and barriers

The second purpose of this report is to make recommendations concerning investment in CEA technologies.

To do this, it was necessary to address the third study question:

What are the enablers and barriers to the start-up and successful operation of CEA enterprises using these promising technologies, and to the overall advancement of CEA in Asia and Africa?

This section presents the study findings related to enablers and/or barriers, with particular relevance to the viable CEA technologies and conditions identified above. The findings are grouped under ten thematic headings.

Start-up costs and access to finance

A quick count of the financial institutions that purport to be interested in investing in food production reveals that there is more than sufficient capital that could be invested in CEA. There are also increasing numbers of microfinance institutions in low- and lower-middle income countries that should be interested in enabling the establishment of CEA enterprises.

However, all the growers who provide training or mentoring on hydroponics/aquaponics reported that the number one reason why course attendees do not start growing vegetables commercially is inability to afford the one-off start-up costs. Table 3 contains the interviewees' estimations of set-up costs for the type of CEA they practice, where available. For those without their own resources or family members who are willing to invest, seeking a loan is often seen as the only recourse. No interviewee mentioned microloans, which may suggest either that CEA is not sufficiently on the radar of microfinanciers. This should be verified with additional research in local contexts.

For standard bank loans, the terms and conditions tend to be problematic because they are not tailored to the sector and do not account for growing cycles.

'You take a loan and you are expected to start paying from the first month, but the only source of income you would get is from the vegetables and the fish which would start giving something back within two or three months. Which means you will have already defaulted on the first two or three payments of your loan.' (James Maina, Greenthumbs CBO, Kenya)

Where farmer loans are available with re-payment schedules aligned to harvest, applicants are usually paired with an expert who determines the loan viability. However, since CEA is not yet well-known or widely-practiced there are no specialist CEA financial risk experts. As a result, CEA start-ups are effectively excluded from loans.

Moreover, loans and grant schemes tend to cover equipment costs only and not the living or welfare costs of a young grower without resources or family support.

'When you give a youth just a month to start their farm and their welfare is not taken care of, it is only a matter of time before they start to spend their investment.' (Samson Ogbole, Soilless Farm Lab, Nigeria)

In Sri Lanka, the interviewees reported that bank loans are becoming more available for hydroponic farming as awareness grows, but they are still more difficult for women to obtain than men. This difficulty was one reason cited for there being significantly more male small-scale hydroponic growers than women, although a provincial subsidy scheme does exist under which 60% of the start-up costs of female entrepreneurs are covered, compared to 50% for men.

Elsewhere, government grants and subsidies for start-up equipment are not always adapted to CEA requirements, meaning that new entrants miss out on financial support. For example, CRAFT Compounds recommends hydroponics systems in 200m^2 greenhouses but the Indian government only offers subsidies for greenhouses of over 1000m^2. These are too large even for many growers using soil-based systems; only around 5% of greenhouses are successful at this scale.

Access to land and enabling land-use policies

In addition to finance, CEA entrepreneurs must have access to some land, albeit less than would be needed to produce the same volume through outdoor agriculture. For example, greenhouses and simple vertical systems can be fitted into quite small back yards or on roof tops. This land should be close to the person's residence; if the land is too far away, it will take too long or cost too much in fuel for the grower to visit regularly, increasing the risk of failure. For city residents, the need for proximity increases costs as urban and peri-urban land is significantly more expensive that land in rural areas.

The existing prevalence of (outdoor) urban agriculture in many low- and lower-middle income contexts is a putative enabler to CEA, in places where the notion of urban residents producing their own food is accepted. In many places, however, there is a tension between urban agriculture for food security and food safety, contamination and nuisance, and land use, particularly in informal settings. CEA might be a useful way to resolve these tensions, given that hydroponic and aquaponic units can be installed on land that is otherwise deemed unsuitable for food production.

However, it should not be taken for granted that commercial CEA systems will be permitted in densely populated areas. For instance, while the Nairobi Urban Agriculture Regulation and Promotion Act 2015 mentioned greenhouses it makes no reference to hydroponics or open vertical growing systems. Peter Chege (Hydroponics Africa, Kenya) believes city governments will oppose plans for urban CEA ventures because of the misconception that chemicals will be sprayed in proximity to residences. He also anticipates safety concerns to be raised over large non-enclosed vertical systems in built-up areas, which can be as high as 20 meters.

Where restrictions on CEA do not exist, there is a likelihood that new rules or standards could be brought in as local governments become aware of the emerging field, and in response to some practitioners using unsafe practices.

'There are not yet any regulatory or policy restrictions to BSF farming in India, because it is very new. But if people are not doing it properly there might be some restrictions later.' (John Ashok, Exocycle, India)

In some contexts, formal growers face legislative barriers to acquiring land. In India, for instance, there is a strict rule that only farmers may buy agricultural land. This policy is intended to prevent land-use change but it can prevent CEA entrepreneurs who are not farmers (such as those seeking a second income), and who do not have any land, from buying a small plot on which to set up a polytunnel or greenhouse.

Those who already own, or can purchase, farmland may find it is not suitable for (some types of) CEA. For example, in many contexts there is no 24-hour electricity supply to farmland. This means growers must choose systems and techniques that do not require continuous artificial lighting, cooling/ventilation, and water pumping, or be able to invest in alternative energy sources such as solar panels.

Market power and differentiation

For some CEA operators – notably the larger Sri Lankan growers, Honest Greens and The Lanka Salad Company – the differentiation they have carved out for their salads and leafy greens, and the control they retain over their marketing, have enabled them to rapidly pivot and remain in business in response to sudden drop in demand from the tourism sector, which was heavily affected by Easter Bombings in 2019 and Covid-19 restrictions on movement, instead supplying high-end supermarkets.

Differentiation and control over marketing channels are far from universal, however, and may be reserved for the larger-scale, more corporate operators. Cucumbers and bell-peppers grown by the Sri Lanka the small-scale poly-tunnel hydroponic growers in Sri Lanka are sold via middlemen on the same market same market as those grown conventionally in greenhouses. Dependence on middle-men meant these growers lost their market overnight, when middle-men stopped visiting due to Covid-19 lockdown.

Several growers in other countries also identified market access as a challenge – or rather, access to the market of their choosing, at the prices they want. In Nigeria and Kenya, for instance, hydroponic/aquaponic vegetables undifferentiated from outdoor- or greenhouse-grown produce, sold alongside it and at the same price.

The lack of differentiation and inability to charge a premium present several problems.

Firstly, they affect the ability of new growers to obtain finance:

'Once there are more buyers, microfinance will be more willing to finance farmers to set up.' (Peter Chege, Hydroponics Africa, Kenya)

Secondly, new entrants (who have not had to obtain approval for bank finance) may have unrealistic expectations, leading to business models that are not economically sustainable, particularly if they are reliant on charging a premium to recoup high set-up costs.

‘At the start people assume that if you have food, people will buy it. But they might not be prepared to buy at the price you thought.’ (Samson Ogbole, Soilless Farm Lab, Nigeria)

Thirdly, growers are unable to maintain price consistency (and therefore a stable income), since despite production of hydroponic/aquaponic produce being more consistent than conventionally-gown it is subject to the same season price fluctuations.

Business risks and secure long-term prospects

The positive image of CEA technologies as a form of white-collar farming that is less dirty and labor intensive than traditional, open-field farming, and that has the potential for high yields serves to attract educated young people. While this may appear to be an enabler, there is a strong risk of disappointment due to unrealistic expectations and under-estimation of the costs.

‘When they come to my training, I tell them the truth is you have to work hard and have deep pockets to sustain the farming and market the vegetables. All together this high-tech farming is as good as any other business or factory, at least in a factory you know the price of the final produce, but in agriculture that is not true the price will go up or down. So, it is a riskier business than a factory.’ (Debo Onafowora, BIC Farm Concepts, Nigeria).

In Sri Lanka, the risk associated with practicing hydroponics was cited as one reason why there significantly more male growers than female: the three polytunnel growers all said women tend to be more risk-averse, considering the need to invest a significant sum of money in set-up.

The inherent risks in working with a new technology, often without adequate support, combined with the lack of an established, differentiated market for produce, means there is not yet a clear career path for young would-be CEA entrepreneurs. This deters some young people, who choose instead to set up in more secure, non-agricultural industries that do not contribute to sustainable development.

‘People are interested in oil and gas as they can see where they will be in 20 years.’ (Samson Ogbole, Soilless Farm Lab, Nigeria)

Training and extension services

The existence of both agricultural universities and agricultural extension services across low- and lower-middle income country contexts has the potential to enable adoption of CEA. At the present time, however, this potential is not realized. The scarcity of training on CEA techniques was a common complaint across several study contexts.

In Nigeria, University students are taught only about open field or conventional agricultural practices. This has implications for would-be CEA entrepreneurs, who must find – and pay for – private training post-graduation, and for prospective employers.

‘You cannot pick graduates fit to run a greenhouse, they are not trained to operate in that industry… so we have to train people afresh to fit into the greenhouse and the hydroponic operations.’ (Debo Onafowora, BIC Farm Concepts, Nigeria)

While this interviewee considered the need to train employees to be a burden, others cited the availability, enthusiasm and learning capacity of young job seekers as an enabler. The Lanka Salad Company in particular paid tribute to the aptitude of the workforce it has trained in CEA, mostly made up of youth from nearby villages.

In a number of case studies, all the country contexts, CEA entrepreneurs were self-taught from the Internet and applied trial and error in starting their businesses. Early adopters tend to be isolated in their locality. One interviewee referred to the 'copy-culture' in Nigeria which may promote proliferation of CEA techniques within communities. However, copying comes with the caveat that doing it wrong, and not receiving support, can have implications both at the household level in terms of lost investment, and also for confidence in CEA as a whole.

Some established operators seek to stem this problem by offering (private) training courses to others, in some cases for free. Aside from costs, however, private training is not always accessible to all prospective growers. Samson Ogbole (Soilless Farm Lab, Nigeria) identified two barriers to participation by young, unmarried women. Firstly, unemployed female graduates are likely to be assigned to household chores. To leave the house, they need the authorization of family members who might be mistrustful of the training proposition or unconvinced by the opportunities in CEA. Secondly, training takes place over several days and accommodation is not provided. This means women must either live close and have transportation or be able to afford safe overnight accommodation.

'Because we are not providing accommodation at all, we realize it is a larger higher roof to scale for women. It is easier for a guy to say, "Anywhere I see I can sleep". For guys who just meet at the venue, they say "Oh we just met we just sleep together and it is fine". But it is not that easy for females. She needs to be sure of security and her comfort.' (Samson Ogbole, Soilless Farm Lab, Nigeria)

Where public training is offered by the Department of Agriculture, it does not always include the latest techniques. For instance, that the absence of specific workshops on aquaponics in Kenya has led some people to try applying techniques learned in workshops on aquaculture and hydroponics workshops, resulting in failures and discouragement (James Maina, Greenthumbs CBO, Kenya). In Sri Lanka, the polytunnel growers believe their yield level is lower than it could be because Department of Agriculture training delivered by Gannoruwa Training Center is not updated with emerging knowledge.

Even when growers have benefitted from some start-up training or guidance, Agriculture Department extension officers in all study contexts have little to no knowledge or technical expertise of CEA, meaning CEA growers do not benefit from the same accompaniment as conventional growers. If growers are not accompanied beyond the initial set up phase there is a very real risk of failure.

'Things can go wrong after the initial set up. Sometimes people report problems too late, or use the system wrong. Especially people who have never grown crops, they don't recognize symptoms of disease.' (Peter Chege, Hydroponics Africa, Kenya.)

R&D funding

Several of the CEA operators interviewed wish to conduct R&D, either to develop their business or to overcome technical problems encountered during operations, but their ability to do so is stymied by lack of access to funding.

For instance, Honest Greens' R&D process to expand its range of leafy greens (with an emphasis on local varieties) is long, painstaking, and expensive; they have to wait an entire growing cycle to see whether each adjustment has worked. External funding would allow them to run more tests concurrently, but as a private company they cannot usually apply for international grants on climate resilient agriculture directly. Rather, they are reliant on the national government to apply and, if successful, disperse funds within the country.

The small-scale BSF sector in Kenya has a number of unmet research needs, including: finding the ideal conditions for optimal egg production; locally-appropriate and affordable methods of preserving the BSF; efficient separation of flies from larvae; and development of various nodes of the value chain. According to Roseanne Mwangi (Sagel Oik Ventures) there are no grant-making institutions targeting the eco- or green economy.

Even where technological solutions exist that would help individual farms overcome operational difficulties, they are often inaccessible because the farmers are not in a position to take out a loan.

'Drying [the BSF larvae] has been a challenge in the production cycle. Good drying requires investment, and that investment hasn't been forthcoming. Production is still not yet at that level where you can say, "My farm is going to get a dryer and we will pay back in so long". It is still one of those development areas where we need support.' (Roseanne Mwangi, Sagel Oik Ventures, Kenya)

Access to technological innovations

The high level of education, technical aptitude, and curiosity of CEA earlier adopters has enabled initial forays into technologies in low- and lower-middle income countries. Some entrepreneurs are entirely self-taught, having learned techniques online, by watching YouTube videos. This also means that they are aware of developing technologies that would assist them in their endeavors – and frustrated at their lack of access. For instance, interviewees in Sri Lanka, Nigeria and Kenya mentioned technologies that would enable improved resource efficiency or better control of parameters, but which are unavailable and/or unaffordable in their countries.

For example, growers would benefit from cold storage systems to reduce post-harvest losses and enable better control of supply-demand, helping to address price fluctuation. According to Samson Ogbole, in Nigeria mobile cold storage units are available that are powered by solar panels rather than the electricity grid, but they are prohibitively expensive for most individual growers.

Peter Chege (Hydroponics Africa, Kenya) mentioned the invention in the United States of tubing that retains water, further reducing water usage as well as power required to pump water around the system.

Samson Ogbole (Soilless Farm Lab, Kenya) referred 3D printing of hydroponic systems; sensors to monitor temperature and humidity; and use of tiny drones to monitor crops in vertical farms.

Access to inputs; existence of value chains

The widespread availability of resources that can be used in CEA operations, such as growing media, as well as the adaptability of techniques to use different materials, clearly enables the start-up of CEA operations and its spread to new localities.

Wherever possible, CEA practitioners in the study contexts use locally-available materials for construction and as growing media. Samson Ogbole (Soilless Farms, Nigeria) actively practices 'asset-based community development' when he travels to new areas to help other people set up farms.

'In every community I look at the assets that they have to determine what to construct. I try as much as I can not to import solutions, so I look for what materials are readily available that I can use.'

In some circumstances, however, local inputs are not available because there is not yet an established value-chain.

For example, Debo Onafowora (BIC Farm Concepts, Nigeria) is frustrated by the lack of coconut production in Southern Nigeria, despite the conditions being ideal. This would provide hydroponic growers with a local source of cocoa peat, which they currently import from other regions, reducing the cost of production.

The need to import seeds is problematic to Samson Ogbole (Soilless Farm Lab, Nigeria), as there are no local sources of seeds adapted to hydroponics and aquaponic growing, while seeds bred in other regions are not optimized for local weather conditions or preferred varieties.

Import regulations

Where local inputs are not available, growers resort to importing them from other countries.

In the experience of Honest Greens, Sri Lanka, government has been open to adapting import regulations as it has gained knowledge and awareness of CEA and its specific needs, in an effort to enable take up. Company representatives said they were initially challenged by restrictions on importing seeds into the country because of concerns about negative impact on local flora and fauna, but these restrictions were eased during their R&D phase.

'Now they have certain exceptions for CEA. We can bring in a certain amount of seeds, under a certain tolerance, under the government purview and they can visit you and see how germination trials and all those things are. They are now opening up but when we started there was no policy,' (Honest Greens, Sri Lanka).

This experience is certainly not universal, however, and there are more examples of intransigent import regulations posing a barrier, due to lack awareness of CEA or lack of understanding of how the needs of growers differs from those of conventional farmers.

For instance, in 2019 Nigeria banned the import of straight fertilizers (i.e. containing only one primary plant nutrient) as a measure to combat insurgency; nitrate is a key component of bombs. However, CEA practitioners rely on straight fertilizers that they use to formulate nutrients for their systems. Compound nitrogen-phosphorous-potassium fertilizers used by conventional outdoor farming is not suitable.

'This probably came about because someone said, "fertilizer is being produced in Nigeria, why should it be imported?", but with no understanding that it is not the same type. This has caused a lot of headache, the cost of production tripled because of what I have to spend to get these fertilizers. People are now smuggling them into the country.' (Debo Onafowora, BIC Farm Concepts, Nigeria)

Peter Chege of Hydroponics Africa (Kenya), meanwhile, faces difficulties in shipping the nutrients he formulates to projects in Rwanda and Uganda. In this case the novelty of hydroponics means nutrients are not yet included in regulatory standards, which can pose problems at customs. Whether or not they are permitted comes down to the decision of individual officers, causing uncertainty for growers.

There are also problems with importing greenhouses into Nigeria, with consequences for start-up CEA growers. Greenhouses are not widely manufactured in the country; BIC Farm Concepts' plan to make greenhouses for hydroponics had to be abandoned due to high costs and the difficulty of obtaining

UV coverings. While there is zero duty on imported greenhouses, each application letter must be signed by the Minister of Agriculture in person. As a result, there is a bottleneck of applications and would-be importers must devote considerable time to lobbying the Ministry.

Waste policy

The existence of unmanaged organic waste can be a driver for certain forms of CEA, notably BSF farming. This is particularly the case for Sanergy, which built its business model around managing human waste, with greater marketing focus on this part of the business than on the animal feed and compost outputs.

Other, smaller players did not tend to see providing systemic solutions to waste problems as part of their business. While both Segal Oik in Kenya and Exocycle in India waste streams that are available on-site (pig excrement and chick carcasses respectively), both also need to bring in additional waste from outside. Their ability to obtain suitable material from dumps or waste sites depends on the practices of waste collection operatives, sorting or separation policy, and public awareness of the value of waste.

Roseanne Mwangi Sagel (Oik Ventures, Kenya) reported that waste is not generally seen as a resource in her region, and people are very quick to discard both organic and inorganic waste together without considering how they could be utilized.

When segregated organic waste is available in the required quantities, BSF farmers still face challenges in transporting it to their sites because it is bulky and it is messy to haul.

Conclusions relating to enablers and barriers to CEA

From the above it is concluded that African and Asian countries have the necessary ingredients for growing the CEA subsector into a significant complementary adjunct to open field agriculture, notably in terms of: (micro) financial institutions' purported interest in agriculture; existing practice of (outdoor) urban agriculture in some contexts (subject to regulations); a young workforce that is seeking white-collar jobs that are less dirty and labor intensive than traditional agriculture, and that is willing to learn and apply STEM skills; established agricultural universities and agricultural extension departments; and local resources that can be used in CEA, including by-products of other industries and organic waste.

However, the study uncovered significant barriers, both to the start-up and successful operation of CEA businesses and to the wider take-up of technologies in these contexts. These relate to: financial institutions' awareness and knowledge of CEA and suitability of finance options; lack of access to land in some settings (and lack of access to land with an electricity supply); planning exclusions due to poor understanding of what CEA entails; lack of a secure, stable market for produce; inherent business risks and lack of secure career prospects; lack of specialist, up-to-date training and extension support for CEA techniques; where private training is available, perceived propriety and safety for women attendees; lack of R&D funding to solve problems encountered; lack of access to affordable emerging technologies; lack of supply chains for some essential inputs, in some contexts; import regulations for seeds, nutrients, and greenhouse materials in some contexts; and poor separation of waste, which is not viewed as a resource.

While the previous section identified the types of CEA that merit investment, it is imperative that that investment be directed towards harnessing the enabling factors and removing the barriers. Failure to do so will result in the potential of CEA to contribute to the sustainable development goals of SAI remaining untapped.

4. Recommendations

The following recommendations are made with a view to harnessing enablers and overcoming specific barriers to successful entry and operation of CEA businesses that were identified in section 3.5. They may be applied to the CEA techniques and conditions identified in section 3.4 as meriting investment to advance SAI in Africa and Asia.

That said, it is assumed that viable models of CEA will be identified and defended by credible investor pitches, in keeping with the principle the type, systems and control parameters in CEA must be tailored to local contexts. This appears to be a relatively safe assumption in view of increasing number of successful CEA enterprises and the certainty that the demand for not only food but for safe, healthy nutritious food will inevitably continue to increase in both Africa and Asia.

Investment recommendations

Financing of new CEA businesses that includes living costs

Financial institutions including banks, micro finance institutions and parastatal agricultural finance agencies (such as the Agricultural Finance Corporation in Kenya) should invest in people as well as equipment by designing innovative debt financing models specifically tailored for entry-level, small-scale CEA practitioners. The enabling features may include:

i) provision for both equipment to set up operations and for welfare and living costs over an initial period, so that new starters can cover everyday expenses;
ii) a payback period that is customized to hydroponic/aquaponic growing cycles with repayments beginning after the activity starts to be profitable;
iii) in cases of contract farming, three-party agreements are required between lenders, borrowers, and buyers, with the latter guaranteeing a market for the borrower's produce.

Debt financing for CEA start-ups will be facilitated by the relevant financial institutions gaining expertise in CEA to be able to conduct appropriate due diligence and assess the viability of applicants' proposals.

They should also remove the barriers to women obtaining loans to start their businesses by, for instance, not requiring permission from male relatives, supporting people with lower literacy levels to complete the application processes, and conducting outreach to improve women's financial education so that they will be aware of and able to take advantage of the financial services that are available to them.

Dedicated schemes for developing sustainable business models

Grant-making bodies, NGOs and commercial financial institutions that work in Africa and Asia should develop dedicated CEA agribusiness/agripreneur programs and incubators under their agricultural development programs.

In addition, organizations could provide preferential schemes (e.g. grants or loans) tailored to the needs of women, young people, and applicants from disadvantaged social groups that could benefit from the less arduous nature of CEA or activities within the supply chain. Local governments and NGOs may provide support by identifying eligible recipients and facilitating their applications.

Career development incentives

Extension and financial agencies could encourage new CEA practitioners by, for example:

i) providing free training where the best students can win start-up funds (including ring-fenced money to cover 6 months' salary);
ii) awarding practitioners at different stages for developing their CEA businesses or exploiting innovative markets.

The incentive schemes may have more social impact if there are specific awards for women and applicants from disadvantaged social groups.

Removal of trade barriers

National governments should invest in development of CEA through removal of tariff and non-tariff barriers to importing essential CEA equipment and implement straightforward, accessible processes for benefiting from the changes.

Support for supply chain development (inputs and equipment)

Agriculture departments, economic development agencies, and private equity investors should invest in development of supply chains to ensure availability of inputs and equipment for CEA, including growing media, materials for CEA equipment, and greenhouse construction. They may do this through, for example: business support and mentoring; business incubators (such as the African Agribusiness Incubators Network (AAIN); and tax breaks.

Seed companies, privately-owned laboratories should invest R&D funds in the development of seeds for varieties that are optimized for CEA in specific contexts, bearing in mind demand for traditional local varieties. Such research could be supported by publicly-funded research institutes, and NGOs that support seed breeding by farmers.

In the specific case of BSF farming, local governments and waste and environmental management authorities should encourage investment in BSF farming as a win-win waste management solution and facilitate operations by, for example:

i) ensuring waste streams are available for BSF micro-enterprises through facilitating co-location on or near to waste processing facilities;
ii) providing equipment and protocols for systematic separation of organic and inorganic waste within facilities;
iii) developing backwards circular economy models that combine collection of organic waste with the delivery of fertilizer products to people who need it; conducting outreach and awareness raising on waste valorization and the need for separating waste at household level.

Support for post-harvest value chains (processing, storage and distribution infrastructure)

Agriculture departments, economic development agencies, and private equity investors should invest in post-harvest processing facilities for CEA-grown produce, including storage and distribution infrastructure (to reduce loss and enable better supply-demand management). They could do this through, for example: business support and mentoring; facilitating access of new CEA enterprises to business incubators.

Support for organization of CEA practitioners

Development organizations and NGOs may provide support for CEA practitioners to organize into associations or cooperatives (local, regional or national), so as to optimize their access to investors who are unable to deal with individuals. Organization should also enable peer-to-peer support, facilitate supply chain development, and allow practitioners to collectively identify their needs and be able to lobby their governments to address them.

Public-private partnerships for CEA clusters or tech-hubs

Governments and private businesses should form public-private partnerships (PPPs) for the development of regional CEA clusters or tech-hubs where growers can work collectively or in close proximity, allowing them to share experiences and information (e.g. on optimal technologies, disease management), leverage economies of scale on equipment and inputs, and market collectively (with increased bargaining power). Establishing these clusters would require significant investment in infrastructure (structures, provision of electricity, water, etc.), mechanisms to make land (public or private) available, and incentives for growers to move to the area (e.g. tax reduction for initial periods; and business support). PPPs may include powerful supply chain actors such as supermarkets or landowners, or successful overseas CEA operators that wish to enter emerging markets for business reasons or to share their expertise as part of corporate social responsibility program.

Funding demonstration CEA installations in schools and universities

National governments or NGOs could provide funding for facilities and equipment for demonstrating CEA installations in schools and universities, as well as teaching materials, to be included in school and university curricula, as exemplified by INMED. This applies to:

- agricultural universities that are training the next generation of farmers;
- technical and non-vocational universities that can train students in specific STEM (science, technology, engineering and maths) skillsets for service and maintenance of CEA facilities and other supply chain roles;
- primary and high schools that may install demonstration hydroponic or aquaponic units to inform and engage students (and their parents) and to teach STEM skills, as well as to provide a source of food for students and the local community.

Investment in training and extension services

Agriculture departments should invest in providing training for farmers on CEA that is tailored to specific local needs, and is regularly updated to include emerging technologies so that the latest knowledge reaches people in low- and lower-middle income countries. They should reach out to farmers, and encourage attendance by ensuring that they are organized in convenient places and times. In addition, agriculture departments may develop relationships with agencies such as INMED that, as noted above, are skilled in taking aquaponics to rural communities and youths.

Agricultural extension services should invest in training extension agents in CEA techniques so that they can identify problems post-set up and know how to help. They should provide continuous professional development to ensure their technical knowledge is up to date. New extension models may also be developed to facilitate knowledge exchange between early adopters and extension officers, as well as formalized direct peer-to-peer exchange between early adopters and new starters.

Investment in awareness and market development

Agriculture departments (local, regional, national depending on division of responsibilities) should dedicate resources to building their own awareness of CEA and be able to disseminate it among farmers and buyers to support the development of stable marketing channels for hydroponic and aquaponic produce.

Research funding on optimal techniques

Public institutions should fund research by local and/or international universities / agricultural research centers on reducing energy consumption, reducing costs, development and use of less synthetic nutrients, and more efficient approaches using new technologies. Ideally this research will be in partnership with local CEA growers who could trial the new techniques.

Overseas trade and development programs

Governments of countries with strong CEA sectors should consider including CEA in their official overseas trade and development programs. This could include–funding exchange visits between practitioners for hands-on learning. This will encourage and facilitate private companies – especially leading CEA companies and technology developers in high-income countries – to invest in new (low- and lower-middle income) markets where their solutions can be adapted and adopted to suit the local contexts.

R&D technology trials in low- and lower-middle income contexts

Technology developers in high-income countries could dedicate part of their R&D budgets to involving growers in low- and lower-middle income countries in trialing their inventions. This would help to ensure that the inventions are optimized for these contexts, including leveraging local climatic conditions (such as sunlight) and taking account of limitations (such as inconsistent energy supply), and to provide access to new developments as early as possible. Where equipment costs cannot be reduced to be immediately affordable by small-scale producers in Africa and Asia, technology companies could help by devising hire-purchase schemes that would enable operators of limited means to access equipment immediately.

Particular needs include arrangements to enable access to technologies that CEA operators may try to do without despite their potential advantages. These include equipment to monitor or survey crops, and equipment for post-harvest processing, (such as BSF larvae dryers).

Policy recommendations

The existence of an enabling policy environment is essential to attracting investment especially for supply chain and market development that will ultimately enable CEA to become a self-supporting sector. The following policy recommendations are directed at national, regional and local governments in low- and lower-middle income countries in Africa and Asia.

1. National and regional governments should adopt integrated policies that promote adoption of CEA, including:

    - commitment to, and mainstreaming of, CEA within agricultural development policy, including provision of funding and extension capacity;
    - inclusion of CEA producers in food security and nutrition strategies;
    - recognition of opportunities within employment strategy, including the need to develop suitable skillsets for all supply chain roles;
    - identification of CEA as an activity within land use policy.

2. National governments should develop evidence-based industry standards and regulations, through cooperation between relevant government departments, the private sector, and NGOs to ensure they are conducive, relevant and appropriate. These will enable farmers to plan their activities and support a good reputation for the sector. Early development of standards and regulations will pre-emptively discouraging harmful or fraudulent practices and avoiding excessive or punitive regulations in the future. Standards and regulations should be reviewed at regular intervals to take account of technological developments.

3. National governments should also establish regulatory standards on the nutrients required in hydroponic growing to be used as a reference for customs inspections to avoid unwarranted import bans or tariff inconsistency.

4. National, regional or local governments (as appropriate) should design processes for obtaining permits to practice CEA (where required under regulatory frameworks) that promote ease of doing business – which, in other words, are quick, straightforward and inexpensive.

5. Local governments should take into account CEA in local planning frameworks, including:

    - setting out specifications on CEA within zoning ordinances and/or urban agriculture regulations so that there is clarity on what is permitted and where;
    - setting out health and safety standards applicable to food production and handling in controlled environments;
    - integration of CEA into spatial design and building codes;
    - developing supportive infrastructure, such as energy and water provision, cold-chain storage and transportation to market.

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Annex 1: Sources of data for CEA case studies in low- and lower-middle income countries

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Annex 2: Case study details

The case studies below are synopses of the interview transcripts and supplementary documentary sources, to provide an overview of each operation.

The Lanka Salad Company, Bangadeniya, Sri Lanka

Interviewees: Charlie Hancock, Debbie Rolmanis

About: The Lanka Salad Company was founded in 2012 by Dutch entrepreneurs, but has been run by Capital Agri since 2019. The company has a local staff of around 30.

System and parameters: The company grows hydroponic lettuces, other leafy greens (rocket, minuza), herbs, and bell peppers using the NFT system in ten 400m^2 purpose-built greenhouses, with steel frames and plastic coverings. The plants are grown using natural light only (although the company is monitoring light levels over a 12-month period in order to do a cost-benefit analysis on supplementary LED lighting). Temperature control is through a pad and fan evaporative cooling system, with corrugated pads against one wall of the greenhouse over which water is continuously circulated and drawn into the greenhouse by exhaust fans. Data on the condition of plants is gathered and analyzed on a daily basis, and adjustments are made to the nutrient solution as required.

Set-up costs: Start-up costs for the greenhouses operated by The Lanka Salad Company are estimated at US$100/m^2 for initial greenhouses ($40,000 for a 400m^2 greenhouse) and US$20,000 ($20,000 per greenhouse) for subsequent units once the infrastructure has been established.

Crops and market: Previously 95% of produce was sold to the tourism market (restaurants, hotels, resorts) in Sri Lanka and The Maldives but since the tourism sector was affected first by the 2019 Easter bombings and then by Covid-19, the company re-positioned to have an additional focus on high-end retail. It also sells salad via its website for home delivery to a small number of residences in Colombo; a 120g pack of mixed lettuce sells online for LKR 399 (around US$2).

Yield, revenue, and operating costs: At any one time the company has 150,000 lettuce plants, 7000 herb plants, and 6000 leafy greens under cultivation, at different stages in the growing cycle. Each greenhouse has a yield of 700kg. Detailed operating costs were not shared, but produce is sold at a minimum 20% margin.

Honest Greens / Urban Agri (Pvt), Colombo, Sri Lanka

Interviewees: Aneeshan Tyagarajah, Sanuja Cooray, and Ashish Advan

About: The company was founded in 2015 by three friends, but it only started commercial operations in 2019 following R&D, piloting and scale-up, with funding from the World Bank and low interest bank loans. The company employs 25 people (including the three founders), with a balance between sexes. They generally hire people aged between 20 and 30, who can handle the labor and are easily trained in more technical matters.

System and parameters: Honest Greens claims to be the only commercial-scale, fully enclosed and climate controlled hydroponic farm in Sri Lanka. The building was purpose-built, and uses LED lighting and ventilation/air conditioning, powered by the electrical grid. The hydroponic method is ebb and flow; control parameters (using proprietary software developed in-house) were not disclosed.

Set-up costs: The interviewees declined to share start-up costs, beyond saying it was ‘a large sum’.

Crops and market: The company grows several types of lettuce, kale, arugula, Swiss chard, basil, pak choi, and is experimenting with new varieties all the time, based on market demand, pricing, costs, a likely yield. The main market is high-end; initially they catered to the tourist market, but after the tourist market collapsed following the 2018 Easter Sunday bombings, they pivoted by launching their own brand and listing in supermarkets. When Covid-19 lockdowns closed the supermarkets and hotels for 3-4 months, they launched an online home delivery platform.

Yield, revenue, and operating costs: Interviewees declined to give details of yield, but said they grow modularly depending on requirements and have a lot of excess capacity. They also declined to share revenue or operating costs for competitive reasons because they have spent considerable time and money finding a profitable model.

S. Ranasignghe, Hydroponic Farmer, Sri Lanka

About: The (male) farmer began growing hydroponic vegetables in 2001 at the age of 50, while working as a school teacher, with support of a project implemented by University of Ruhuna, Sarvodaya Foundation and South Asia Inter Media Unit. He has no employees, but labor is provided by himself and family members.

System and parameters: He grows vegetables in a 2000 square ft (186m^2) polytunnel with a polythene roof and nylon fabric netting on the side walls using a drip irrigation system and natural sunlight. The system protects crops from excess rainfall and pests, but they experience occasional fungal attacks and can be damaged by excessive heat.

Set-up costs: The set-up cost was nearly LKR 600,000 (c. US$7170) in 2000; at 2021 prices the same set up is estimated to cost LKR 100,000 (c.US$5000).

Crops and market: The main crops gown are bell peppers and salad cucumbers, which are sold to middle-men for sale at Manning Market in Colombo.

Bell peppers: The polytunnel houses 800 plants, providing a yield of 2kg/plant. The duration of the bell pepper crop is 9.5 months, including a harvesting period of 6 months. The total cost of production is about LKR 200,000 (US$1,000) for 2000 sq. ft cultivation, including the cost of pumping water, but without the cost of family labor (120 days). The price of bell pepper ranges from LKR 200-1200/kg (US$1 – 6), with an average of LKR 500 (US$2.50), giving an average net income in a season is LKR 800,000.

Salad cucumber: The duration of the salad cucumber crop is three-months, giving a harvest for 1.5 months. The cost of production is LKR 120,000 (US$600) for one round, not including family labor (30 days per cycle).

P.K. Samarasinghe, Sri Lanka

About: The (female) farmer began growing hydroponic vegetables in 2017, with support from the Department of Agriculture. She has no employees, but labor is provided by herself and family members.

System and parameters: She operates four 93m^2 polytunnels with UV resistance polythene on the roof (to filter the light) and net on the walls. The structures protection from rain and pests, and minimizes crop damage and food loss compared to conventional systems; the only light source is sunlight.

Set-up costs: The start-up cost for a 1000 sq. ft. tunnel is with ordinary polythene costs nearly LKR 350,000 (US$1750) and LKR 500,000 to 600,000 (US$2500 – 3000) with UV polythene at 2017 prices.

Crops and market: The crops cultivated are salad cucumber and bell pepper. The crops are sold to a middleman at the farm gate, who sells them in Manning market in Colombo as garnishes and food decorations in food service. There is no local demand for salad cucumber or bell peppers.

Yield, revenue, and operating costs: Salad cucumber: The operational cost of growing salad cucumber is around LKR 35,000 (US$175) to grow 200 plants in an area of 1000sq.ft. excluding the labor cost of the farmer. One plant provides 6-8kg of yield amounting to a total average yield of 1600kg. The price of cucumber ranges from LKR 100-200 (US$0.50 - $1) that would generate a net income of LKR 210,000 (US$1051) in a season, without the value of family labor.

Bell pepper: The operational cost for bell pepper is LKR 75,000 (US$37m5) for 1000 sq. ft. to cultivate 350-400 plants without the value of labor, and one plant gives nearly 1-3Kg of yield. The estimated value of labor contribution is LKR 150,000 (US$750). Bell pepper price ranges from LKR 400-1200 (US$2 – 6). The average net income from bell pepper cultivation is around LKR 500,000 (US$2500) excluding the imputed cost.

K. Chaminda Rangana, Sri Lanka

About: The (male) farmer began growing hydroponic vegetables in 2012, after seeing a neighbor's successful hydroponic farm. He received support from his neighbor and from the Department of Agriculture. He has no full-time employees but does employ a laborer to help with the initial potting stage.

Structure and parameters: He grows vegetables in four polytunnels of 1500sq ft (139m^2), 1500 (139m^2) 1000 sq.ft (92m^2), 1300 sq.ft (120m^2), with UV polythene roofs and net side walls. Sunlight is the source of light which is controlled by using the UV polythene. The polythene and nets also controlled the pest and disease infestation while protecting the plants from rain. He uses a fertigation unit with a drip system to provide fertilizers. Groundwater is pumped to meet irrigation requirements. The average water requirement per plant is one liter per day. The structure, methods and parameters enable high productivity, with high quality and quantity of vegetables, and less need to use pesticides.

Set-up costs: The start-up cost was LKR 450,000 (US$1150) for a 1000 sq. ft. polytunnel that included a drip system at 2012 prices. He uses a fertigation unit with a drip system to provide fertilizers. Groundwater is pumped to meet irrigation requirements. The average water requirement per plant is one liter per day.

Crops and market: The crops grown are bell pepper and salad cucumber, grown in alternate seasons; he is also cultivating capsicum as a new variety. The vegetables are sold to a middleman, who sells them at Manning market.

Yield, revenue, and operating costs: Bell pepper takes 100 days to grow and provides harvests up to six months. One plant gives an average 1-1.5 kgs of bell pepper. 400 bell pepper plants can be cultivated in 1000 sq.ft polytunnel area (he uses a 100 sq. ft and a 1300 sq.ft polytunnel for the peppers). The total operational cost is LKR 115,000 (US$575) excluding the value of the farmer's labor input. The price of bell pepper ranges from LKR 150 to 2000 (US$0.75 - $10), providing a gross income of LKR 850,000 (US$4256) in a season without imputed cost.

Cucumber takes 35-45 days to grow and provide a harvest for 45 days. The farmer is cultivating cucumber in two 1000 sq. ft polytunnels. One plant gives nearly 4-6Kgs of yield. The number of plants grown in an area of 1000 sq ft is about 200. The operational cost of salad cucumber is LKR 60,000 (US$300) without the value of labor contribution. The average income earned in a season from cucumber cultivation is LKR 450,000 (US$2253) excluding family labor values.

Craft Compounds Ltd, Navi Mumbai, India

Interviewees: Vijay Yelmalle, Ajay Singh

About (including crops and market): CRAFT started out in 2000 as the Centre for Research in Alternative Agri-Technologies, through which founder Vijay Yelmalle conducts research on optimal hydroponic and aquaponic parameters (including use of Gro lights, different medias, use of technology) and reducing set-up costs, and offers training at weekends. The commercial company, CRAFT Compounds Ltd, has two brands:

- Rural IDEA (integrated and digitalized economical aquaponics) is the business-to-business brand through which it partners with marginal farmers to establish small (300m^2) hydroponic or aquaponic farms (leveraging the findings of CRAFT research), providing training and a guaranteed market to sell the produce. The company buys the vegetables from the farmers, takes out the costs (for the seeds, fingerlings, fish management support, technical support, the sage, etc.), then gives the remainder back to the farmer. Aquaponic farmers sell the fish for additional income themselves.

- Mystiq Garden is the consumer brand for the online sale of boxes to customers in Mumbai, with an entry into retail and the B2B trade anticipated for the future. The company also runs a small café served by a dedicated hydroponic unit to provide diners with ultra-fresh salads. The target market is the wealthiest 1% of the population of Mumbai (around 200,000 people).

System and parameters (including yield, revenue, and operating costs): Under Rural Idea the company currently runs five microfarms – 3 aquaponic and 2 hydroponic.

1) A 500m^2 ground-based aquaponic farm producing bell peppers, jalapeno peppers, leafy vegetables, and heirloom tomatoes, and rearing tilapia and bass. Leafy vegetables are sold at INR110, providing annual revenue of INR 790,000 (US$10,970), with operating costs of INR 400,000 (US$5550). Net profit is around INR 390,000 (c US$5470) a year.

2) A second aquaponic farm producing leafy vegetables, we have herbs like basil, peppermint, and mustard greens; it produces 5 tonnes of vegetables a year and 2 tonnes of fishes a year.

3) Another aquaponic unit using the raft system with gravel as the medium, which produces spinach, coriander, fenugreek, kale, cucurbits. Yield is 5 tonnes of leafy vegetables and 2 tonnes of tilapias or bass.

4) Two greenhouse hydroponic farms growing cherry tomatoes in rows, using coco peat as medium, with an annual yield of 7 tonnes. Each cucumber sells for around INR 70 (c. US$1), which translates to US$70-80 per kg.

On its Mystiq Garden website, the company states that is uses sensors for measuring air and soil temperature, humidity, atmospheric pressure, monitoring pH levels, ammonia, nitrate and nitrite levels. The sensors are monitored using mobile phone applications. It also states that it uses drones and robots to improve data collection.

Set-up costs: Currently it costs around US16,100 for an aquaponics system, but the company is doing research to reduce the cost to around $10,750. No costs were discussed relating to the sensors, drones and robots.

Exocycle, India

Interviewee: John Ashok

About: Exocycle works in association with a New Zealand company called Hexacycle Ltd. The company has a parent BSF farm in the Indian state of Kerala; Ashok is commissioned to establish new BSF farms across the country. The interview focused on set-up of BSF operations at a broiler chicken farm in the state of Tamil Nadu.

System and parameters: The BSF farm is housed inside a disused chicken shed, with two layers of netting covering the sides for ventilation and to keep out birds and insects. Optimal mating temperature is 23°c. The system consists of 3,000 trays on which the larvae are raised; a dark cage for the pre-pupae or pupae; a large, net-covered mating room with wooden strips for the laying of eggs. The eggs are collected as they hatch, and the neonates put into new trays. The main inputs to the system are i) organic wase from the nearby vegetable market; ii) dead birds from the hatchery that have been rendered, put through the hammer mill, and chopped. The two waste products are mixed to form the substrate for the BSF larvae. The plant will have the capacity to process about 3 tonnes of organic waste per day, with each tray of larva requiring 5kg a week.

Set-up costs: Use of an existing concrete structure has significantly reduced set-up costs to around US$12,000. The main costs have been purchase of the plastic trays for the larvae (3,000 trays costing US$4 each). The adaptation of the structure and construction of various cages costs around $3,000.

Crops and market: Dried BSF larvae will be used by the chicken farm as a protein source for the birds, instead of more expensive soya oilcake. The compost produced by the larvae will be used for the cultivation of maize on-site, with excess sold to the market in 20kg bags. [check price].

Yield, revenue, and operating costs: The plant has a capacity of 3 tonnes of BSF larvae. The main operating cost is the wages of 4 or 5 laborers. Collection of waste from market will entail minimal costs because the same trucks will collect the waste on the return journey from delivering broiler chickens.

Greenthumbs Cbo, Nakuru, Kenya

Interviewee: James Maina

About: Greenthumbs CBO was founded in 2014 by a group of young people who are all interested in agriculture, but who have main jobs in other areas (e.g. accountancy, pharmacy, plumbing, insurance, beauty and fashion). Greenthumbs CBO has 10 members currently, 4 men and 6 women. As a community-based organization (CBO), the primary mission is to contribute to making the world a better place for the youth and the vulnerable populations through agricultural and other social entrepreneurship projects.

System and parameters: The organization grows indigenous leafy vegetables and tilapia fish in an aquaponic system housed inside a greenhouse, with side netting for ventilation. The fish tank contains 2000 tilapia. The vegetables are grown in timber raised beds containing local pumice, with only $10m^2$ of growing space. Spring water is pumped (using a solar pump) from the fish pond to the raised beds, and back again. The only light source is sunlight. However, the organizers are currently part of a 'living lab' research project with Wageningen University and the Bakia Foundation, through which it will develop new, more efficient methods. This may include using pyramid structures for the vegetables, which will enable more growing space but still benefit from sunlight.

Set-up costs: The interviewee did not provide start-up costs for the system, but said the aim is to enable cheap replication by local farmers

Crops and market: The main market for vegetables and fish a local hotels and households. The vegetables are more expensive than conventional vegetables, because there are limited vegetable imports in the area; the fish is sold at the same price as those imported from other towns (but cheaper than those imported from outside the country). The organization plans to start processing/value addition of the fish.

Yield, revenue, and operating costs: Monthly yield is 200 tilapia and 100kg of vegetables (including conventionally grown vegetables from outside the aquaponics system), which brings in revenue of around KES 30,000 (c. US$300) a month. Costs are hard to quantify because not all inputs are needed every month; only the fish feed is constant, with an expense of KES 5,000 (US$45) per month.

Hydroponics Africa, Zambezi (Near Nairobi), Kenya

Interviewee: Dr Peter Chege

About: The company was started in 2014 by Peter Chege, a chemist who developed an interested in formulating nutrients for hydroponic systems that are adapted from Western models. The company's main business is in provision of five different models of simplified hydroponics systems (over 6800 systems have been installed to date), as well as running a training farm (with post-training support) and providing consultancy to NGOs.

Systems and parameters: The systems – which range from small wall-mounted units for those with no land, to household units to feed five or 6 people, to units of 130m^2 upwards for small-holder farmers. At the upper end are large commercial, modular systems for people with over five acres of land. The systems are designed to depend on shade nets for ventilation, to use locally mined media, and to draw up water using osmosis rather than requiring a pump. The only light source is the sun, and the vertical, A-shape units can be as high as 20 meters.

Set-up cost: An example is a commercial farmer who has 130m^2 hydroponic system for growing tomatoes. The initial installation costs US$2,000, including the seedlings and nutrients (but not including a structure, such as greenhouse).

Yield, revenue, operating costs: Running costs for the next year would be US$3 per month; 500 tomato plants would each produce at least 10 kg of tomatoes, for a total yield of 5 tonnes. Tomatoes sell at a minimum of US$ 0.6 per kg, meaning that the farmer will almost recoup their costs within the first 12 months.

Sagel Oik Ventures, Makuyu, Kenya

Interviewee: Roseanne Mwangi

About: The Sagel Oik BSF operation is located on a pig farm. Mwangi began raising BSF in 2019, with technical support from the INSFEED project (*I*nsect feed for poultry, fish and pig production in sub-Saharan Africa), a project jointly funded by the Australian Centre for International Agricultural Research and Canada's International Development Research Centre. She also offers training to local people who are interested in raising BSF, and runs a YouTube training channel.

System and parameters: The BSF operation is based in a purpose-built greenhouse on a concrete base and open sides covered with netting, to optimize the temperature. The system consists of plastic crates (0.5cm x 0.75cm) containing substrate for the larvae, and adult fly cages (90 x 90 x 120cm) containing wooden 'eggies' for them to lay eggs on. The substrate is made up of pig manure combined with other organic waste, such as potato peelings from a local potato processing plant. The main parameters monitored are temperature (optimal mating temperature is 23°c) and humidity (around 50%).

Set-up costs: The greenhouse constituted the main set-up cost as it was purpose-built; Mwangi was not able to provide details of cost. A key cost variable is the quantity of greenhouse paper used.

Crops and market: The outputs of the system are live larvae which Mwengi feeds directly to her pigs, dried larvae that are sold to other farmers; and compost.

Yield, revenue, operating costs: The BSF plant has a daily yield of 220 – 250kg of live larvae. Dried larvae are sold for c. KES100 a kg (US$0.90)[8]; the price is tied to that of fish meal, as it must be equal to or cheaper than alternative animal feed. The operating cost is directly related to the waste stream that is used, including the cost of transporting waste to the site. However, for Mwangi this is off-set

[8] Typical live:dry weight ratio for Segel Oik's BSF exploitation was not discussed but online source put the acceptable weight of dry larvae at 25 – 35% of live larvae (EAWAG, n.d.)

by cost savings of not having to purchase expensive feed for her pigs, as well as the ability to take them to market sooner due to their high protein diet.

Bic Concepts, Lagos, Nigeria

Interviewee: Debo Onafowora

About: The company was founded by social entrepreneur Debo Onafowora, who was motivated by the lack of production of tomatoes in the southwest of the country due to inclement soil conditions to develop a commercial hydroponic farm in Lagos. In addition, he supplies equipment and inputs for hydroponic production and provides training for new starters.

System and parameters: The majority (95%) of crops on the commercial farm are in high tunnel greenhouses (about 5% are under shade outside, and 1% are completely open). The method is responsive drip irrigation, the only light source is sunlight, and ventilation is provided using high side nets of over 2 meters high; some greenhouses have gothic open roofs for the hot air to exit. A limited number of circulation fans and shading nets are also used for some crops, to manage heat and light intensity.

Crops and market: The main crops produced are tomatoes, kale, lettuce and peppers. Onafowora has also grown animal fodder hydroponically; he believes that fodder centers near cities could be instrumental in resolving clashes between farmers and nomadic herdsman whose animals damage grazing lands.

Costs: A basic greenhouse/polytunnel hydroponic system of 240m^2 costs around US$10,000, including the tunnel structure and covering (accounting for $8,000), substrate, troughs, irrigation system, seeds (high quality hybrid seeds), hydroponic nutrients and fertilizers.

Yield, revenue, and operating costs: On average, the 240m^2 system can produce about 1.5 tonnes of pepper a month (about equivalent of the yield from 1 hectare of land using conventional methods. Over 6 months, this production would yield revenue about US$4,000 ($700-800 a month).

A 240m^2 farm costs between US$150 and $200 to operate on a monthly basis, including salary of a farm operator of around $100 a month. Six months' supply of nutrients costs $2,000, and seeds cost $200 for 1000.

Soilless Farm Lab, Abeokuta, Ogun State, Nigeria

Interviewee: Samson Ogbole

About: The main business of the enterprise is its hydroponic farm. It also offers training, mostly for free, as a way to give back to the community, and Ogbole travels to help people set up farms in other locations.

System and parameters: The hydroponic systems are housed in greenhouses. They use both ebb and flow and the Kratky method that is modified from NFT; instead of circulating water around the system, it remains still. This uses minimal electricity (less than two hours of power are required a day). Initially they started with aeroponics but the need for constant electricity in a place with regular power outages (and therefore need for a back-up battery) was too expensive.

Crops and market: The main crops produced are lettuce, cabbage, celery, parsley, spinach, tomatoes, peppers. There are four commercial models: i) sales to aggregators, who re-sell vegetables alongside produce from other farmers; ii) distributors who buy branded produce from the farm for re-sale; iii) nutritionists who have their own food companies producing ready-baked trays, salads, fresh meals; iv) people who place orders from our website. The enterprise is working to ensure produce is sold for a constant price year-round, as far as possible.

Ogbole also sees potential in growing fodder crops for cattle farming, to reduce the strain on the land.

Set-up costs: Set up costs depends on where the farmer is; Ogbole basis his advice on asset-based community development, which means he looks first at locally-available materials and inputs. Depending on whether the system is monolayer or vertical, the kind of crop, and any special needs, a 182m^2 unit will cost an average of US$2000.

Yield, revenue, and operating costs: Using the example of lettuce, 100g sells for US$0.20 (1kg for $1). With a monthly yield of 2000 plants in 182m^2, this produces revenue of US$400 a month. Celery, meanwhile, sells at the higher price of $4 per kg; it also continues to grow after planting, which means there is less need to spend on seed.

Operating costs depend on the crop; for lettuces exclusively, the cost of power can be around $130 per month, and nutrients $50. Once salaries are factored in, running costs are around £300, leaving a $100 margin.

Annex 3: Sample semi-structured interview guide

The interview guide was slightly adapted for ease case/type of CEA operation. The interviews were semi-structured so there was scope to follow-up with additional questions where necessary.

Part 1: Questions about the farm:

1) When did you start your farm?

2) Please can you describe the structure, methods, and parameters used in as much detail as possible? (E.g., Is the system in a polytunnel or fixed building? If fixed building, was it purpose built or renovated? What are the construction materials? Is it mono-layered or vertical? What is the precise type of hydroponics that you practice? What is the energy source(s)? What is the lighting type (e.g. artificial, sun)? What parameters do you control (such as heating, lighting, ventilation, etc.)?

3) What were the start-up costs?

4) What is the growing space in m^2?

5) What produce do you grow?

6) What is the monthly yield?

7) What is the monthly revenue?

8) What inputs do you need? What are your monthly operating costs?

9) What profile of customers do you market to?

10) How does your produce compare in price to conventionally grown vegetables (locally-grown and imports)?

11) Do you have any employees? If so, how many and what are their job profiles? What is the gender balance? Is there a reason for this?

Part 2: Viable types and parameters

1) Why did you choose this structure, methods, and parameters described in part 1?

2) How well suited are they to the local context and challenges – e.g. environmental factors, resource availability, etc.?

3) Are these the best choices for optimum production efficiency?

4) Would you do anything differently in retrospect?

Part 3: Questions about challenges and potential support

Thinking first about when you first started up:

1) What difficulties did you face when you started? What difficulties do new starters face today?

2) Did you experience any difficulties as a result of your gender, age, education level, ethnicity, socio-economic group, or any other factors?

3) What help did you get to start up, from whom (private sector, public sector, NGOs)?

4) Is there any other kind of support that new starters would benefit from (from the public sector/governments; or private businesses/investors)?

5) Are there any groups to whom this support should be targeted (e.g. women farmers, particular social groups, etc.)?

Now thinking about your operations in general:

6) What operational challenges have you faced in the past? Do you continue to face?

7) What is the reason for them?

8) Are there any local or national government policies that help you? Have hindered you? Why? (Bear in mind gender, age, education level, ethnicity, socio-economic group, or any other factors that could lead to exclusion through policy bias.)

9) Are there any innovations that have helped you (in technology, policy, finance, institutions)?

10) Any other changes, improvements, or innovations that you see could be helpful?

Part 4: In what ways can CEA contribute to key development goals?

What are the specific local development-related challenges? *(e.g. food insecurity and nutrition; social equity; poverty reduction; resource use e.g. water, land, fossil fuels, energy); natural environment; resilience to climate shocks and stresses)*

1) Which of these challenges does your farm help to address? How?

2) Can you quantify the impact in some way?

3) How could impact be increased?

4) What are typical profiles of farmers who are interested in hydroponics in Sri Lanka? (e.g. age, gender, socio-economic status, etc.)?

5) Why are these people most interested?

6) If women are not among those who are interested hydroponics, why is this the case?

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