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ORIGINAL PAPER

Controlled-environment agriculture for an urbanised world? A comparative analysis of the innovation systems in London, Nairobi and Singapore

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Abstract
Multiple crises and challenges in the food sector are driving a rising need for innovative food production methods that could provide a growing urban population with high-quality, sustainable and healthy food while strengthening the resilience of food systems. Controlled-environment agriculture (CEA) in urban areas has been proposed as one possible pathway to address these demands. Despite its various potential benefits, CEA is still in a conceptual or experimental stage and there has been less research that focuses on the specificities of urban areas where it could be implemented. Using the Urban Food Production Innovation System (UFoPrInS) concept, this paper analyses the urban contexts and enabling and impeding factors for implementing CEA in three contrasting locations: London, Nairobi and Singapore. Based on document analysis and semi-structured expert interviews, our findings show that Singapore is a favourable location because public policies support the implementation of CEA to reduce food import dependency and enhance the resilience of food supply. In London, high food import dependency is increasingly seen as problematic, but the implementation of CEA has been hampered by other policy priorities. In Nairobi, where over half of the population lives in informal settlements without adequate food, water and sanitation, CEA is unlikely to make an economically efficient contribution to food security. We conclude that the implementation of CEA might be suitable in locations with ample capital and knowledge, stable political, social, and infrastructure conditions, and limited space, where value can be linked to hospitality and tourism, supported by positive pricing for resource savings.

Keywords Urban food production systems · Resource-efficient food production · Innovation system · Institutional framework · Systemic problems · Case study analysis

1 Introduction

Concerns about the sustainability, resilience and resource availability of food production are growing around the world in the face of long-term stresses arising from biodiversity loss, climate change (Nellemann, 2009; Specht et al., 2019), urbanisation (Nam & Pardo, 2011; Ojo et al., 2016; FAO, 1989; Willett et al., 2019), and a growing world population, and disruptive shocks such as the Russian assault on Ukraine (Glauber & Laborde, 2022; von Cramon-Taubadel, 2022) or the Covid-19 pandemic (Lal, 2020; OECD, 2020). Among the large range of innovations to address these challenges, controlled-environment agriculture (CEA)[1] has gained much attention (Benke & Tomkins, 2017). CEA is an umbrella term for a range of novel production systems that have in common the indoor, climate-controlled production of plants, animals and/or mushrooms. Proponents claim a range of "potential advantages as a clean and green source of food, along with biosecurity, freedom from pests, droughts, and reduced use of transportation and fossil fuels" (Benke & Tomkins, 2017: 13). The related concept of vertical farming

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[1] All acronyms used in this publication are summarised and explained in Appendix A.

(VF) emphasises the efficient use of land by producing food in high-rise buildings (Beacham et al., 2019). CEA and VF have been enabled by technological developments in the areas of energy supply, LED lighting, culture beds, plant nutrients, sensors, information processing, automation, artificial intelligence and the Internet of Things (IoT), many of which are also transforming outdoor farming (Khan et al., 2021). The combination of these new technologies allows the creation of "plant factories" (Shamshiri et al., 2018) or aquaponic systems for the combined production of fish and plants (Wirza & Nazir, 2021).

The option to produce food in urban locations is a conspicuous element of the CEA and VF narrative. CEA and VF have become part of urban agriculture (UA) strategies (Marini et al., 2023). However, while the literature on CEA and VF is full of links to urban food production, it contains little consideration of the specific urban contexts where such operations would be implemented. A recent review of the CEA literature "observed a paucity of research on the socio-economic aspects of CEA" (Dsouza et al., 2023: 1). In contrast, a review of research about urban and peri-urban farming identified the Internet of Things (IoT), resilience, CEA, plant factories, Life cycle assessment (LCA), and VF as "prominent trends" (Srinivasan & Yadav, 2023), confirming the dominance of technological aspects. As a result, little is known about the dynamics and effects of implementing CEA in urban contexts and whether they live up to the promises of CEA proponents. A case study of New York found limited positive effects on employment and the availability of fresh produce (Goodman & Minner, 2019). A historically informed analysis of several cases of VF concludes that "despite their high yields, the extremely high capital investments needed to build the precise controlled environments of today's vertical farms preclude the profitable production of staple crops, rendering them unlikely to fulfil their land-sparing promises" (Bomford, 2023: 879).

The prospects of CEA as a contribution to sustainable urban food production depend on context factors and policy support. A literature review on the promotion of sustainability in UA found large variation in "numerous socio-economic and environmental contextual factors in cities, especially when comparing realities of the Global North and Global South" (Bennedetti et al., 2023: 1). While the literature on city-level policies on UA and CEA is limited, a recent comparative study of European cities found significant activities by cities but great variation in context and policy: "the policy instruments were shaped by different local governance and institutional structures as well as by the local actors and community practitioners and their growing interest in UA/CEA" (Marini et al., 2023: 1). CEA was generally not the focus of urban food strategies, and allotment gardens were better supported compared to other types of UA (Marini et al., 2023). A recent literature of public perception of CEA found that "consumers are still uncertain about indoor food production, mainly due to the lack of naturalness" (Mina et al., 2023: 1), but could be persuaded by credible and visible social benefits such as "increased fresh food supply, social integration, revaluation of urban areas, educational opportunities, and added value in terms of the local economy and job creation" (Mina et al., 2023: 1). Hence, "indoor farm projects must integrate different functions and carefully evaluate the context in which they are set" (Mina et al., 2023: 9).

This paper adopts an innovation system (IS) perspective to analyse the conditions under which CEA can be implemented in urban contexts. An IS denotes the entirety of "[…] all economic, social, political, organisational, institutional factors" (Edquist, 2005: 182) and their relationships, which are involved in the creation, diffusion and implementation of scientific or technological knowledge (Lundvall, 1992; Malerba, 2002). We hypothesise that CEA IS differ significantly between urban locations regarding in particular the relevant actors and their relationships, the prevailing institutions and available resources, and that these differences affect whether and which types of CEA are implemented. Specific locations pose varied challenges and opportunities, such as a constraining or enabling institutional framework (Curry et al., 2014; McEldowney, 2017) or the degree of social acceptance (Milicic et al., 2016; Specht et al., 2016).

The confluence of technological and city-specific aspects has been captured by the concept of an "urban food production innovation system" (UFoPrInS) (Dietze & Feindt, 2023) to analyse the contexts for integrating CEA in large cities. To assess the influence of different UFoPrInS characteristics and the enabling and constraining factors for the implementation of urban CEA, we compare three contrasting cases (London, Nairobi and Singapore) to address the following research questions:

1. What are the characteristics of UFoPrInS in London, Nairobi and Singapore and how do they differ?
2. What factors in these three cities influence the development of the UFoPrInS and the implementation of urban CEA innovations?

The paper contributes to current debates about the potential of CEA in urban locations to address local food system challenges. It also creates conceptual and empirical linkages between the literatures on CEA and IS. The remainder of this paper is structured as follows: Section 2 presents the conceptual framework. Case study selection, data collection and analysis are explained in Section 3. Section 4 presents the results, followed by their

discussion in Section 5. Section 6 provides conclusions and an outlook.

2 Conceptual framework: Urban food production innovation systems (UFoPrInS)

The IS perspective was developed to understand the elements and dynamics that are involved in specific innovation processes (Edquist, 1997). These differ *inter alia* by sector, country (e.g. Lundvall, 2007) or even region (e.g. Cooke, 2002). The implementation of CEA in urban locations requires a unique combination of actors, relations and institutions that combines elements of Agricultural Innovation Systems (AIS) (e.g. Hall et al., 2006; Kilelu et al., 2013), Technological Innovation Systems (TIS) (e.g. Carlsson & Stankiewicz, 1995) and Urban Innovation Systems (UIS) (Athey et al., 2007; Markatou & Alexandrou, 2015). The UFoPrInS concept captures the specific characteristics of urban CEA IS and highlights the significance of institutions and the urban environments (Dietze & Feindt, 2023). A UFoPrInS consists of five key dimensions:

- The individual and collective actors involved in the development or implementation of the food production innovation;
- The network relationships between these actors;
- The exchange of resources (knowledge, mutual access to networks, financial and material resources, goods and services) between the actors;
- institutions, i.e. 'rules of the game' (Edquist, 1997), which include
  - Formal institutions, in particular laws and regulations, financial institutions, requirements and markets (the regulation of supply and demand);
  - Informal institutions (i.e. habits, routines, values and preferences);
- Local residents who are not part of the network of actors developing or implementing the innovation, but who can influence the innovation process through acts of acceptance, support or resistance (Dietze & Feindt, 2023).

These elements are embedded in a social, environmental and institutional context (Prové et al., 2016), which varies from country to country and often within countries (Nelson, 1993).

The analysis begins with the identification of the innovation and the contributing *actors*. However, understanding and substance of an innovation often change when the innovation process moves from conceptualisation to development and implementation, reaching higher levels of technological maturity and broadening the networks of contributing actors (Dietze & Feindt, 2023; Putra & van der Knaap, 2018). This also applies to the 'urban' character of the innovation. CEA operations are not necessarily drawn to urban settings. Despite the spatial compactness in particular of VF, high opportunity costs of space in cities are a challenge for CEA. Furthermore, not all actors of a CEA innovation network – those who participate in the conceptualisation, development and implementation of the innovation – are necessarily located in the urban location where a food production innovation is implemented. The actor network of the urban CEA IS likely extends beyond the boundaries of the specific city (Burt, 2000; Fichter, 2009).

Network relationships between the actors in an IS can be either formal or informal, direct or indirect (Lin et al., 2023; Wang & Xu, 2023). It is possible that multiple, overlapping networks contribute to the development and implementation of an innovation. Network constellations tend to evolve over time in response to internal dynamics, evolving needs, and changing external circumstances. Changes affect the composition and internal constellation of networks, the quality and density of relationships, the exchange of resources, the relative power of actors within the network, and the ability of networks to achieve desired goals (Kernecker et al., 2021; Klerkx et al., 2012).

During the innovation process, the significance of various *resources* exchanged between actors is likely to fluctuate. For example, in the development stage, technical know-how holds particular importance, while design expertise, capital investment and access to distribution channels are typically required for the implementation stage of a food production system (FPS). The necessary expertise and skills for operating an urban CEA can be gained via training programmes (Wieczorek & Hekkert, 2012). *Institutions* hold significant importance as they shape actors' cognitive and normative expectations, albeit without fully determining their behaviour (Bergek et al., 2008; Edquist & Johnson, 1997). Rules are interpreted and continuously challenged and negotiated between actors during interactions. Over time, the actions of individual and organisational actors inevitably impact the perception and comprehension of rules, thus contributing to institutional stability or change (Giddens, 1984). This implies that institutional change is typically evolutionary and not necessarily the result of the intentions of particular actors, although deliberate efforts to modify formal or informal institutions are feasible.

Residents are particularly important for urban CEA systems due to the high spatial density of cities. Consequently, spatial segregation, commonly used as a strategy to avoid unwanted neighbours and negative externalities, is often more complicated and expensive (Dietze & Feindt, 2023). In addition, urban residents play a crucial role as primary customers. The expectations of innovation

network actors concerning the attitudes and behaviour of residents affect decisions regarding the substance, design and location of food production innovations (Markatou & Alexandrou, 2015).

During the innovation process, diverse *systemic problems* can arise that hinder the successful development and functioning of an IS (Bergek et al., 2008; Wieczorek & Hekkert, 2012). These systemic problems can be related to 1) the presence and capabilities of the actors (e.g. relevant actors are absent or actors lack necessary competencies), 2) the presence and quality of the infrastructure (e.g. relevant types of infrastructure are absent or inadequate or dysfunctional), 3) the presence and quality of interactions (e.g. interactions are weak or too exclusive) and 4) the presence and quality of institutions (e.g., relevant institutions are lacking, too weak or too rigid) (Klein Woolthuis et al., 2005; Wieczorek & Hekkert, 2012).

The exploratory analysis of the CEA IS in London, Nairobi and Singapore through the lens of the UFoPrInS framework aims to better understand how local IS characteristics affect the prospects and development of urban CEA.

3 Materials and methods

3.1 Comparative case study approach

Comparative case studies are useful to gain a deeper understanding of the prevailing contexts for novel and complex phenomena within and across different settings, where little or no knowledge exists (e.g. Baxter & Jack, 2008; Flyvbjerg, 2006; Goodrick, 2014; Yin, 2017). A selection of contrasting cases is generally used to identify relevant factors that can explain different outcomes. To scrutinise the characteristics and contexts that enable or hinder the implementation of urban CEA, we selected London, Nairobi and Singapore, which represent very different economic, institutional and social contexts.

3.1.1 London

London is of one of the largest financial centres in the world (Greater London Authority, 2021a) and has the highest number of educational institutions in Europe (Greater London Authority, 2008; Kendall, 2020). Despite high average levels of wealth, food insecurity is a concern in the UK (Ingram et al., 2013). Many of London's approximately 9.1 million residents (Trust for London, 2021) rely on food banks and are unable to access nutritious, affordable and high-quality food (DEFRA, 2020a; Greater London Authority, 2018). In 2022, 18.1 per cent of London households experienced food insecurity, with households containing children displaying greater levels of insecurity compared to those without children (London Assembly, 2023).

Following its withdrawal from the European Union (EU) and its Single Market (called Brexit), the United Kingdom (UK) is currently repositioning itself in terms of regulation and trade relations. The UK government has declared its ambition to create a profoundly innovation-friendly society and transform London into a "Singapore on the Thames", but has since abandoned this idea (Davies, 2019; Lydgate & Anthony, 2022). However, Brexit has led to a surge in food prices, further exacerbating poverty (Plickert, 2022). At the same time, the UK's food system is struggling with negative environmental impacts that need to be addressed (e.g. climate change, biodiversity loss) (Dimbleby, 2021).

The UK food system has been heavily dependent on food imports since the mid-19th century. Imports come from 160 countries, with almost 60% of fruit and vegetables being imported from continental Europe (Dimbleby, 2020). Recently, many voices have argued that the UK food system needs to be transformed to insulate it from the vagaries of long supply chains and make it more resilient to external challenges (Dimbleby, 2020; Greater London Authority, 2010). UA niches have been well-established in London, with a particular focus on community gardens or allotments (Wascher et al., 2015). UA is typically practiced in private residential gardens or communally managed allotments (Grafius et al., 2020). The latter are the most important form of UA in the UK (Acton, 2015; Crouch & Ward, 1997). About 52% of the land utilised for UA in the UK is dedicated to allotments (Edmondson et al., 2020). UA became particularly important during the Second World War, when the government initiated the 'Dig for Victory' campaign to encourage local people to grow their own food (Crouch & Ward, 1997; Martin & Marsden, 1999). In recent years, UA and high-quality "organic" food production have regained interest in the UK in the face of rising food prices (DEFRA, 2010; Wascher et al., 2015), Brexit (Kendall, 2020) and the Covid-19 pandemic (Dobson et al., 2021). Accordingly, also various innovative forms of CEA, such as VF, plant factories, and container farming, have been established in London (Jans-Singh et al., 2019; Tapper, 2019).

3.1.2 Nairobi

Nairobi, with the highest rate of urbanisation and population growth in Africa (UN-Habitat, 2005), faces a precarious local food supply situation due to factors such as increasing food and fertiliser prices, droughts, climate change, high-energy costs and competing demands for agricultural land that negatively affect food production and supply (Republic of Kenya, 2011). The Covid-19 lockdown worsened this issue, resulting in supply scarcities and impaired food security (Ikua, 2020; Schupler et al., 2021). Many residents

of Nairobi struggle to obtain sufficient nutritious food (Republic of Kenya, 2011). As of 2022, Nairobi was home to 5,119,000 people (United Nations, 2022) in a total urban area of 696 km^2 (World Population Review, 2022). By 2050, it is estimated that Nairobi's population will reach 14.3 million (Hoornweg & Pope, 2014). High levels of migration from rural areas to Nairobi (Lee-Smith & Memon, 1994) contribute to increased poverty, uneven urban development and increased food insecurity (Cashman, 2018; Lee-Smith & Lamba, 2017). Roughly 60% of Nairobi's population reside in informal settlements (Oxfam, 2009), which exhibit the most inadequate health and institutional status of all population groups in Kenya, owing to deficient sanitation and the absence of basic services (African Population & Health Research Center, 2014).

Land and water scarcity are two significant agricultural challenges in Nairobi, which hinder food production performance (FAO, 2018). To mitigate land scarcity and increase food production, there has been an adoption of innovative food production technologies like vertical, rooftop or greenhouse farming, and container gardens (Nairobi City County, 2017). At present, numerous innovative urban food production (UFP) forms such as sack gardening or multi-storey gardens can be found in Nairobi. These forms are located in backyards, home gardens, and garden plots in public open spaces, as well as in informal settlements and slum areas of Nairobi (Foeken & Mwangi, 2000; Gallaher et al., 2013). They have been utilised by private households and small-scale farms to increase self-sufficiency and mitigate high food prices (Cashman, 2018; Foeken & Mwangi, 2000; Wascher et al., 2015). In addition to small-scale food production, there are also instances of large-scale agriculture in the peri-urban areas of Nairobi that have become part of the city's expansion (Foeken & Mwangi, 2000). Even though CEA has not been widely established in Nairobi, there are already some examples of such systems (e.g. hydroponics, aquaponics) implemented in Kenya (Croft et al., 2014; Dijkgraaf et al., 2019).

3.1.3 Singapore

Singapore is a highly urbanised city-state situated on a small island in Southeast Asia, ranking as the third most densely populated country globally (Statista, 2023; WorldAtlas, 2021). In 2021, 5.45 million residents inhabited an area of 719.2 km^2 (Singapore Department of Statistics, 2021). By 2030, the population is projected to increase to 6.5 million inhabitants (The Business Time, 2018). Food insecurity is a prevalent problem in Singapore, especially among the unemployed, with 10.4% of the country's households facing food insecurity before the Covid-19 pandemic (Nagpaul et al., 2020).

Singapore has transitioned from an emerging to a mature economy over the past 60 years, boasting one of the highest per capita incomes and cost of living. The city-state has a dynamic and successful market economy with a strong focus on services. Only ten per cent of Singapore's total land area is suitable for food production (Wood et al., 2020). In 2018, 13% of vegetables, 9% of fish and 24% of eggs were produced domestically (Singapore Food Agency, 2018). Singapore heavily relies on imported fresh water (around 60%) (Leiding & Hustiak, 2019), energy (over 95%) (EMA, 2017) and food (around 90%) (Wood et al., 2020).

To address the increasing demand for high-quality food, to reduce costs and dependence on imported food, and to enhance resilience to external disruptions, such as environmental disasters and pandemics, the government of Singapore has sought to increase domestic food supply (Teng, 2020; Wood et al., 2020). The '30 by 30' strategy aims to increase local production to 30% of the country's nutritional needs by 2030. To accomplish this ambitious goal, Singapore is investing extensively in research on novel food production solutions (Singapore Food Agency, 2020; Wood et al., 2020). Funding is provided for CEA (e.g. hydroponics, aeroponics and aquaponics) and novel food (e.g. alternative proteins) that promise resource-efficient and space-saving food production (Singapore Food Agency, 2020). Various forms of UA and CEA (e.g., VF, aquaponics, hydroponics, aeroponics, insect farming) have been incorporated into towering structures, on rooftops, or in multi-story car parks (e.g. Mok et al., 2020; Wood et al., 2020; Zareba et al., 2021).

3.2 Data collection and analysis

This paper follows a qualitative research design to obtain detailed information on our hypotheses and research questions (Creswell, 2014; Kalu & Bwalya, 2017). To gain robust evidence of the contexts and the UFoPrInS as CEA IS of each site, we combined a qualitative content analysis of scientific and grey literature with semi-structured expert interviews. The content analysis was conducted as a systematic review procedure (e.g. the PRISMA statement – Preferred Reporting Items for Systematic reviews and Meta-Analyses). The PRISMA statement provides a checklist comprising 27 items and a four-stage process for reviewing relevant literature, which involves 1) identifying literature, 2) screening the literature, 3) checking for eligibility, and 4) selecting the final corpus of texts (Liberati et al., 2009). Our document search and selection involved a pre-defined search strategy, the screening of extracts from the datasets and the reporting of the results. Such a literature review offers a well-established way of summarising existing research in a particular field (Snyder, 2019).

A variety of search terms were used to identify relevant literature with a particular focus on the institutional framework for implementing CEA in London, Nairobi and Singapore (see Supplementary Material A). Scopus and Web of Science were selected as databases for the scientific

literature as these are the largest and most recognised databases of abstracts and citations for academic research (Baas et al., 2020). Additionally, relevant grey literature not covered by Scopus and Web of Science was identified through the usage of Google Scholar, where, however, the search results might be affected by personalised algorithms.

The search query on 1st September 2022 was limited to publications published between 1990 and 2022, as earlier publications are unlikely to be relevant for CEA. In Scopus, Web of Science and Google Scholar, 1723 publications were identified for London, 209 publications for Nairobi and 1536 publications for Singapore. The titles, abstracts, and keywords of the publications were manually screened and determined to be relevant if they contained content related to our research subject. Publications focusing on environmental sciences or other case studies were excluded, resulting in a text corpus of 79 publications for London, 21 publications for Nairobi, and 104 publications for Singapore. The full text of the publications was then scanned for eligibility based on predefined inclusion and exclusion criteria. Publications that included explicit statements regarding the structural characteristics of urban CEA IS of our selected case studies were incorporated. This step left 51 publications for London, 18 publications for Nairobi and 17 publications for Singapore. Using the snowball principle, we included publications and grey literature suggested by colleagues or interviewees or identified through a Google search of the respective ministries' websites. The final sample of 57 publications for London, 25 publications for Nairobi and 23 publications for Singapore was analysed through systematic content analysis, using a deductive coding strategy with codes derived from the research focus (see Appendix B). The analysis of the final sample comprised: 1) characteristics of the UFoPrInS and 2) enabling and constraining contextual factors for the implementation of CEA in London, Nairobi and Singapore.

Semi-structured interviews were conducted with experts in each location to gain a deeper understanding of the CEA IS in each case study area. In line with our research hypothesis, these expert interviews focused on identifying relevant elements of the CEA IS, critical factors, public perceptions, barriers, and catalysts, as well as the institutional framework for implementing CEA in London, Nairobi and Singapore. Experts were selected through purposive sampling based on their subject-specific expertise (Meuser & Nagel, 1997; Rapley, 2014) in researching, developing, implementing and operating CEA systems. Their experience and competence were key factors in the selection process. The interviews were conducted with experts from four sectors: policy, academia, civil society organisations (CSOs) and CEA practitioners. Countering difficulties in obtaining interviews with policy and administrative actors, we employed snowball sampling (Rapley, 2014), wherein interviewees were requested to propose other experts who could provide insights into our research focus. Overall, we contacted 66 experts in London, 78 experts in Nairobi and 50 experts in Singapore. They received an interview invitation letter outlining the study goals. Experts were asked to demonstrate their willingness to participate in an interview by responding via mail and specifying their available dates. We received responses from 34 experts in London, 37 experts in Nairobi and 27 experts in Singapore. Despite repeated follow-up requests, no response was received from the remaining experts. In the results section, statements from the interviews are marked as IL_xx for London, IN_xx for Nairobi and IS_xx for Singapore, where "xx" indicates the running numbers of each interview. In total, we conducted 12 expert interviews in London, 16 in Nairobi and 11 in Singapore online via Zoom between April and September 2021. At this point, theoretical saturation was reached (Baur & Blasius, 2014).

All interviews followed the same semi-structured guideline, with mostly open-ended questions and minor adaptations for each site. The interviews lasted between 45 and 60 minutes. The guideline consisted of three parts to answer our hypothesis and research questions. The first part aimed to get an overview of the context and the current state of UFP in each site. The second part introduced the CUBES Circle concept as an anchorage example of a CEA innovation currently in development. CUBES Circle aims to develop a modular system for the combined production of plants, insects and fish, with a zero-waste approach where the residues from one production system are fed into another. Tailored connections to the urban environment aim to close material and energy cycles (CUBES Circle, n.d.). The questions aimed to assess the potential for CUBES' hypothetical implementation in the local context and focused on identifying formal and informal institutions relevant to CEA more generally. The third part assessed the main barriers and catalysts to, and public attitudes towards the implementation of CEA. All interviews were recorded and manually transcribed and then anonymously analysed, using qualitative content analysis (Gläser & Laudel, 2008). A deductive and inductive coding scheme was employed. Most of the deductive categories were derived from the literature and the analytical framework, while additional codes were added inductively based on insights gained during the analysis of the

Table 1 Relevant actor groups and perceived role for implementing CEA in London

Actor group	Reported functions related to the implementation of CEA
Public sector actors	• Creating a supportive regulatory framework • Providing financial initiatives • Promoting research
Value chain actors	• Implementing CEA systems • Providing the local community with CEA food items
Private sector	• Providing healthy and quality food to vulnerable people • Assisting in the efficient development of CEA • Financial backing • Raising awareness of CEA among members of society • Advisory services on the implementation of CEA
Civil society organisations	• Promoting and training of food growing activities
Knowledge institutions	• Conducting research and development • Diffusing knowledge
Actors in urban environment (e.g. community leaders)	• Providing support and access to networks and institutions

Source: Author's compilation (2023) based on the expert interviews (n = 12) and Dimbleby (2021), Dobson et al. (2021), Edmondson et al. (2014), Fuldauer et al. (2018), Greater London Authority (2018), Hasson (2019), Jans-Singh et al. (2019) and Kendall (2020)

interviews (Bortz & Döring, 2015). The coding scheme was repeatedly discussed and refined by the authors.

4 Results

4.1 London

4.1.1 Actor constellation in London

The CEA IS in London is characterised by a variety of actors involved that are particularly relevant to the implementation of CEA (see Supplementary Material B), including public sector actors (policy makers and administration), CSOs, the private sector and value chain actors (VCA) that fulfil various roles in implementing CEA in the urban setting (see Table 1). Policy makers play a crucial role in supporting various types of UA. This requires establishing a regulatory framework that supports UA and specifically urban CEA (IL_02, IL_09, Dimbleby, 2021; Kendall, 2020), offering financial incentives (Edmondson et al., 2014; Fuldauer et al., 2018), and encouraging research in food technologies (Fuldauer et al., 2018). New agricultural policies and funding programmes are being developed with the support of devolved administration, which is increasingly considering high-tech innovations in food production (Jans-Singh et al., 2019; Kendall, 2020).

London represents an environment with thousands of different VCA, comprising growers, producers, manufacturers, caterers, retailers and fast-growing technology companies, all ostensibly committed to the provision of high-quality, nutritious, and sustainable food to the local population (Greater London Authority, 2018). VCA could potentially serve as adopters of urban CEA (IN_02, Jans-Singh et al., 2019):

> *"I think that a mainstream retail food supplier like Waitrose […] getting involved and investing is really big news. I think that you need the government but also you need business. And, if you've got major supply chains investing in this stuff, then that's really good news. So, I would say that's an exciting thing from my point of view (IL_02: 15-18)".*

In recent years, there has been a growing interest from CSOs in UA, including urban CEA (Jans-Singh et al., 2019), with the aim of investing more funds in this area to bolster the number of green circular economy jobs in London (Greater London Authority, 2018). The main food growing networks in London are the *Capital Growth* network, which advocates and provides training for food growing activities (Greater London Authority, 2021b), and the *Sustainable Food Cities Network* in the UK, signed by 52 cities which are committed to expanding UA (Dobson et al., 2021).

Additional actor groups, comprising the private sector (IL_01, IL_09, IL_10), knowledge institutions (IL_09), and urban actors, like community leaders (IL_05, IL_10), were identified as important for implementing CEA in London. Table 1 illustrates the different roles undertaken by these groups. These actor groups support the implementation of CEA in different and sometimes interrelated ways. However, there is some fragmentation of collaboration between knowledge institutions and CEA entrepreneurs (Fuldauer et al., 2018; Kendall, 2020).

4.1.2 Institutional framework in London

Formal institutions in London The UK's regulatory framework reflects responses to past and current challenges facing the food sector, from reliance on food imports since the mid-19th century (Dimbleby, 2020, 2021) to the UK's entry into the EU and its *Common Agricultural Policy* in 1973 (Dimbleby, 2021; Hasson, 2019). Over the following decades, EU agricultural policy shaped the UK food system by influencing what and how food was grown (Benton et al., 2019).

Leaving the EU in 2020 started a transformation of the UK's food policy framework that will continue until 2027 (Benton et al., 2019; DEFRA, 2020b, c). The food system of the UK has been interlinked with the EU in five key areas: funding (e.g. Common Agricultural Policy (CAP) direct payments), intra-EU trade, labour, EU regulations (e.g. novel food regulation), and extra-EU trade. Due to Brexit, numerous EU policies need to be transposed into UK law, particularly those relating to food and agriculture policies and trading arrangements (IL_01, IL_02, Benton et al., 2019; DEFRA, 2020a; Lydgate & Anthony, 2022). This situation has increased uncertainty for local entrepreneurs (IL_01, IL_02). In the case of insect farms, the UK's exit from the EU created a legal limbo. While edible insects were previously subject to *Regulation (EC) No. 2015/2283 on novel foods*, the UK government eliminated regulations and licensing requirements for their sale. To continue operating, existing insect production companies are now obliged to demonstrate the safety of their products, irrespective of previous approval under EU regulations (Horizon Insects, 2021; Ridler, 2021). Departure from the EU has not only invalidated EU regulation, but has also changed the nature of governance in the UK. Regulatory processes and functions are currently delegated to UK ministers, without key regulatory bodies such as the Food Standards Agency being enshrined in legislation (Lydgate & Anthony, 2022).

Along with Brexit, the UK government aimed to launch a new food strategy that would (1) better take into account socio-economic factors and trends in diet and health conditions, (2) maintain high environmental and animal welfare standards (Benton et al., 2019; DEFRA, 2020a, c), (3) support a sustainable, resilient and productive agricultural sector (DEFRA, 2020a) and (4) provide high-quality and affordable food to the local population (DEFRA, 2020c). Despite the implementation of several food-related strategies, such as the 'net zero' emissions agriculture by 2050 strategy, that have the potential to convert the UK's food system into a sustainable, efficient and resilient system (DEFRA, 2020b; Dimbleby, 2021; Graham, 2020), urban CEA has not been explicitly included in the UK legislative framework (see Supplementary Material C) (Howe, 2003; Martin & Marsden, 1999). To address food-related issues, the Mayor of London has introduced the London Food Strategy. The strategy aims to combat child obesity, food insecurity, and climate change by supporting good food businesses, creating partnerships with public sector partners, promoting UA activities, and improving the efficiency and sustainability of the food system (Mayor of London, 2023).

The UK's institutional framework primarily focuses on UA (e.g. urban gardening, allotments, community gardens) and rural farming practices, rather than CEA (DEFRA, 2020b; Dimbleby, 2021; Greater London Authority, 2021b). The *National Food Strategy* emphasises the connection between environmentally sustainable agricultural practices and efficient food supply chains (Dimbleby, 2020) and suggests exploring novel forms of FPS, including vertical farming or insect biomass, to achieve food sector transformation as part of the UK's new *Innovation Strategy* (Dimbleby, 2021). Furthermore, *The Future of Food 2040* report by the National Farmers' Union highlights hydroponics and aquaponics as a viable means of food production. It is recommended that financial incentives for innovative research be increased to promote their adoption (Graham, 2020). There are numerous funding institutions dedicated to improving food production's resilience and sustainability. Their focus primarily lies in improving technological aspects of farming practices in rural areas, such as automated harvesting, drones, and autonomous tractors. However, their attention is not directed towards urban CEA (Kendall, 2020). In this context, the *Environmental Land Management Scheme* (ELMS) was explicitly mentioned in the interviews as relevant to CEA (IL_15). ELMS replaces the direct payments of the CAP, where farmers receive payments for providing public goods. Nevertheless, it does not cover UFP (Kendall, 2020).

Nevertheless, the interviews revealed several laws, regulations, and statutory requirements that may impact the implementation of urban CEA involving fish, plant and insect production, and could involve significant bureaucracy (IL_05, IL_07, IL_08, IL_09, Greater London Authority, 2010):

> *"We can be quite bureaucratic as well. Yeah. So, yeah, sometimes, planning permission […] can take a long time, but that's all relative, I suppose. But the planning process and sometimes need for consultation and public consultation and that can create time loss" (IL_05: 269-272).*

To safeguard technological innovations, the UK offers various categories of intellectual property (IP) rights, depending on the innovation type. These categories include patents, copyright, registered and unregistered designs, trademarks, and trade secrets. Patents, especially,

are frequently utilised to commercially exploit university research (Griffiths, 2023).

Informal institutions in London The Covid-19 pandemic, alongside rising concerns over environmental, ethical and health issues, has brought about changes in *eating patterns* among consumers in London (Benton et al., 2019; Ethical Consumer, 2020; Fisher et al., 2012), which are associated with shifting *values and norms*. This includes growing interest in the ingredients and provenance of food (IL_01, IL_03, Benton et al., 2019) and a demand for more fish products (IL_12, Ethical Consumer, 2018, 2020), local and organic food (IL_03, IL_09), and vegetarian and vegan products (Ethical Consumer, 2020; Graham, 2020).

British consumers exhibit mixed feeling towards CEA. While the Gastón et al. (2021) study and our expert interviews recorded favourable attitudes towards CEA among UK consumers (IL_01, IL_02, IL_04, IL_05, IL_07, IL_09, IL_11, IL_12), other studies found more sceptical attitudes (Ares et al., 2021; Balcombe et al., 2021). The primary factors responsible for UK consumers' rejection of CEA are their perception of it being unnatural and artificial, where food is produced in a non-natural, technological environment (Food Standards Agency, 2020), and the perceived high energy consumption of these systems.

Generally, food choice is influenced by various factors, including price (Ares et al., 2021), taste, sustainability and health concerns (Chintakayala et al., 2018; Graham, 2020):

> *"I think if people were convinced that it was safe, and you could make an argument that there is, you know, it is a closed system, or part of the circular economy or something like that, then people would be very interested in it. I think people are looking for novelty as you know, food is a highly innovative sector, and projecting this as a new thing, and that it is tasty, is healthy, is sustainable, is novel, and I think all of that would work very well" (IL_12: 240-244).*

The role of *cultural context is* also significant. London demonstrates a notable level of cultural diversity, stemming from its past controlling a colonial empire. This led to immigration from various ethnic groups (Garduño-Diaz & Khokhar, 2020), including Africa, Europe, South Asia and the African-Caribbean (IL_03, IL_04, IL_12, Dimbleby, 2020; Garduño-Diaz & Khokhar, 2020).

Perceptions towards insect consumption in the UK remain largely ambivalent (IL_03, IL_04, IL_07, IL_12):

> *"The issue is some kind of acceptance by consumers, I suppose, I think this is quite weak in the UK context. I don't think people do eat insects very easily" (IL_04: 276f.).*

However, it appears that the younger generation in Western societies may be more open to eating insects than the older generation (Graham, 2020; Food Standards Agency, 2020). In order to increase insect consumption, UK consumers could potentially be more inclined to do so if they linked this practice to a healthy way of life (Food Standards Agency, 2020).

4.1.3 Infrastructure in London

The food industry in London has experienced growth, with 69 food tech start-ups established in the city in 2023 (Seedtable, 2023). These start-ups encompass a wide spectrum including consumer-focused apps and services, food delivery with a partial emphasis on meat alternatives and insect-based products, food manufacturing, food safety guarantees and traceability. Financing is secured from diverse investors and a range of different business, including business-to-business (B2B) and business-to-consumer (B2C) models (Seedtable, 2023).

The growth of UA in London has been linked to several food system improvements, including shorter food supply chains, more sustainability and resilience (Martin & Marsden, 1999), contributing to the UK's target of achieving net-zero agriculture (Dimbleby, 2021), and addressing water scarcity (Greater London Authority, 2010).

However, the establishment of CEA in London may face multiple infrastructure-related challenges (see Supplementary Material F). The main barriers identified in the literature and interviews are:

- Insufficient space within the city (IL_01, IL_07, IL_09, IL_12, Howe, 2002; Greater London Authority, 2010),
- Accessibility and high cost of urban land (IL_01, IL_05, IL_09, Greater London Authority, 2010)
- Comparatively high costs for resources like water and electricity (IL_03, IL_05, IL_09),
- Competition with various other urban land uses (Greater London Authority, 2010, 2021b),
- Unclear land tenure (IL_03) and,
- Lack of long-term land tenure (Greater London Authority, 2010),
- Inadequate financial resources (Greater London Authority, 2010; Kendall, 2020) and
- Lack of skilled workforce for operating urban CEA (Fuldauer et al., 2018; Kendall, 2020).

Table 2 Relevant actor groups and perceived roles for implementing CEA in Nairobi

Actor group	Reported functions related to the implementation of CEA
Public sector actors	• Raising public awareness of CEA • Leasing urban land • Providing advice and crucial information • Legal control and determination of food safety • Providing a supportive legal framework for CEA
Value chain actors	• Distributing food products
Knowledge institutes	• Carrying out research • Training for local businesses • Implementation of urban CEA • Promoting CEA • Networking with key stakeholders
Civil society organisation	• Supporting urban food initiatives
Private Sector	• Investing in CEA

Source: Author's compilation (2023) based on the expert interviews (n = 16) and Abro et al. (2020), Bukachi et al. (2021), Nischalke et al. (2020), Ozor et al. (2021) and Spina et al. (2021)

4.2 Nairobi

4.2.1 Actor constellation in Nairobi

Relevant actors in the CEA IS in Nairobi are public sector actors (e.g. political actors), knowledge institutions, the private sector, VCA, CSOs and actors in the urban environment (see Supplementary Material B). The activities range from soil-based horticulture to insect farming. The latter is seen as generating economic value and creating employment opportunities in Kenya (see Abro et al., 2020; Waithanji et al., 2020). Each of these groups of actors has distinct roles in facilitating the implementation of CEA in Nairobi (see Table 2).

In particular, public sector actors can support the development of urban CEA (IN_02, IN_07) by increasing societal awareness (IN_02, IN_04), leasing urban land (IN_16) or connect relevant actors like the *Food Strategy Directorate* (IN_05). Among them, political actors such as the *Agriculture Food Authority*, the *Ministry of Agriculture and Livestock* or the *Nairobi City County Government* play a crucial role (IN_02-IN_05, IN_07-IN_12, IN_16), as they connect all relevant policy departments and provide guidance and vital information on food safety issues (IN_01, IN_02, IN_08, IN_12). Political actors have varying roles in supporting urban CEA. They can exercise legal control and pronounce on food safety and quality (Bukachi et al., 2021) or enable a supportive legal environment for urban CEA (IN_07, IN_09, IN_11, Abro et al., 2020; Ozor et al., 2021):

> *"[…] the first one is government because of the entire policy element, and then in this case it is trying to be more facilitative and promotional as opposed to just focusing on the regulation. And then that, to me, is still the biggest driver" (IN_11: 54ff.).*

In addition, VCA such as intermediaries, input suppliers, processors, retailers, and consumers, play a crucial role in the success of all forms of UA in Nairobi (IN_02, IN_05, IN_08, IN_10, IN_14, IN_16). For instance, intermediaries distribute food products from producers to different retailers or local markets (IN_08, IN_12, IN_14), making them an essential enabler of UA. If a market is established for UA products such as plants, fish or insects, it could lead to an increase in the number of urban UA initiatives (IN_09, IN_11, IN_13). The group of retailers proves to be of utmost importance in Nairobi with subs-sectors selling food in small street markets, permanent buildings, or larger supermarkets (IN_08, IN_14). Respondents distinguished three groups of consumers in Nairobi: first, households with medium to high income who can purchase larger quantities of food from supermarkets and store at home due to access to refrigerators; second, consumers with very low income living in informal settlements, who are restricted to buying only the amount of food necessary for their daily diets; third, consumers without means to prepare their own food, who purchase their meals from local cookshops (IN_08).

Other significant actor groups include CSO (IN_03, IN_10, Ozor et al., 2021) and knowledge institutes (IN_02, IN_04, IN_10, IN_12, IN_16, Ozor et al., 2021). The Mazingira Institute is of particular importance as it lends substantial support towards the promotion of UA and fosters links between farmers and political entities (IN_01, Nischalke et al., 2020). Foreign direct investment has played a significant role in Kenya's economy, predominantly in the horticulture sector. Associated advantages are the transfer of knowledge, specific technologies, work experience for the workforce or the creation of financial and commercial networks (Spina et al., 2021). Foreign companies were also identified as potential investors in UA projects (IN_07, IN_10).

4.2.2 Institutional framework in Nairobi

Formal institutions in Nairobi The regulatory framework in Nairobi has enabled a broad range of food production methods such as greenhouses, fish tanks, multi-storey gardening, community gardens, sack gardening, and backyard gardening (Lee-Smith, 2010) (see Supplementary Material D). CEA has been included in the baselines, intervention strategies, and resource requirements of the Nairobi City Council. Planning frameworks and crop development plans establish development priorities, programmes, and

strategies, annual targets, expected outcomes, and resource requirements to promote food and nutrition security by adopting urban agricultural technologies (Nairobi City County, 2017).

Generally, Nairobi's institutional framework has undergone three transformations: the transformation that occurred with the begin of colonialism, the post-colonial transformation and the introduction of multiparty democracy in Kenya (Lee-Smith & Lamba, 2000). British institutions had a significant influence on Kenya's institutional framework during the colonial period (Cashman, 2018; O'Neill, 2015). The colonial state regulated food production in Kenya under the imperative of a mercantile-industrial food regime (O'Neill, 2015). While a few instances of UA under colonial rule were noted (Gore, 2018), it was generally dismissed by colonial authorities as they did not perceive it as a crucial component of modern development (Cashman, 2018; Lee-Smith, 2010). After gaining independence in 1963, Kenya's institutional framework underwent various reforms. For instance, it transitioned from a mercantile-industrial food regime to a neo-liberal food regime that involved economic restructuring under external pressures. Government intervention, e.g. in the form of adjustment loans for food and agriculture was gradually phased out (O'Neill, 2015). The constitutional reform, which follow the 2007 post-election violence resulted in a new constitution, which established counties as sub-national governments responsible for specific sectors, including agriculture (Cashman, 2018; Gore, 2018; Heller et al., 2020). UA obtained formal recognition as a valid land use in the *National Land Policy*, the *National Agriculture and Livestock Extension Programme*, the *National Food Security and Nutrition Policy* and the *Urban Areas and Cities Act*. Attempts to develop a comprehensive national policy were impeded by conflicts over responsibilities and priorities within the Ministry of Agriculture (Cashman, 2018; Gore, 2018; Lee-Smith, 2010).

The Nairobi City County Government launched the *Food System Strategy* in 2012 to promote sustainable food production systems in the city and provide Nairobi residents with affordable, accessible, nutritious and safe food by promoting UA (Kamau et al., 2020). This is enforced by the *Urban Agriculture Promotion and Regulation Bill* that was implemented in 2015 from the Nairobi City County Government to strengthen UA in order to enhance food security and to assign land and water resources to the vulnerable, especially in informal settlements (Gore, 2018; Lee-Smith & Lamba, 2017). Despite this ambitious goal, agriculture and environment are separate sectors in Nairobi. The absence of cooperation between these two sectors explains why arrangements for land and water have yet to be made accessible to people in informal settlements (Lee-Smith & Lamba, 2017). Furthermore, existing regulations, encompassing the *Local Government Act*, the *Public Health Act* and the *city by-laws,* pertain to UA activities in a somewhat contradictory manner (Cashman, 2018). Particularly, the keeping of livestock and cultivation or irrigation on public land are prohibited by the *Public Health Act* to prevent any nuisance (Ayaga et al., 2004; Cashman, 2018). Similarly, the *Local Government Act* prohibits unauthorised individuals from cultivating crops on land belonging to private citizens, local authorities, or the government (Cashman, 2018). Consequently, due to this legal ambiguity, "many assumed UA to be illegal" (Cashman, 2018: 45). Meanwhile, the government provides the option of renting land for short-term usage (Ayaga et al., 2004). The insect rearing sector is flourishing in Nairobi (Abro et al., 2020), with regulations authorising the utilisation of dried insect products, such as the black soldier fly, as animal feed composites legally endorsed by the Kenya Bureau of Standards (Nischalke et al., 2020).

The Nairobi City County Government has announced that it will explore CEA as means to enhance food security and mitigate post-harvest losses, among other objectives (Ozor et al., 2021). Additionally, the *County Integrated Development Plan* briefly refers to container gardens as a method to increase production per unit area (Nairobi City County, 2017). Financial support from governmental, private, and multilateral institutions such as the World Bank and the African Development Bank, as well as bilateral financial partners like the German International Development Agency – GIZ, UK's Department for International Development, and FAO is intended to reduce the impact of climate change on agricultural and fisheries practices (Government of the Republic of Kenya, 2017; The World Bank, 2022).

The *Intellectual Property Bill 2020* provides regulation for the protection of IP. Trademarks, patents, industrial designs, and copyrights are the main forms of protection that safeguard innovative and technological advancements (International Trade Administration, 2022; MNO Advocates LLP, 2022).

Informal institutions in Nairobi *Food culture* varies among the different ethnicities and communities in Nairobi (IN_04, IN_05). Influences of British settlement history are reflected in the development of national agricultural policies, the rise of supermarkets, and the fast food industry (Lee-Smith & Lamba, 2017; O'Neill, 2015). In recent years, there has been an increasing market for local, fresh, safe, hygienic, healthy and organic food catering to affluent groups (Bukachi et al., 2021; Wainwright & Wainwright, 2018). Establishing personal connections with local vendors is often seen as crucial to assess credibility and gaining more reliable insights on the source of food (IN_04, Bukachi et al., 2021). For those who can afford it, beef is the preferred meat in Kenya (Heller et al., 2020). Fish consumption in Kenya is typically low, except for inhabitants living near Lake Victoria. When consuming fish, individuals typically prefer those from Lake

Victoria or seawater (IN_04, IN_11, IN_15, van Gorcum et al., 2019). Interviewees report scepticism towards the products from aquaponic systems: *"[…] fish produced from ponds within the city itself will not be the real fish people are used to from, say, for example, Lake Victoria"* (IN_15: 101f.).

Despite the emergence of insect rearing in Kenya (Abro et al., 2020), consumers retain scepticism towards insect-derived food products (IN_04, IN_08). However, interviewees reported general acceptance of insects as feed for fish (IN_03, IN_04, IN_05): *"[…] no one would eat insects, I think one would rather go hungry than eat insects. But if it is for feeding the fish, that's fine"* (IN_04: 234ff.).

Ambivalence has been noted in consumer *behaviour and attitudes* regarding the acceptance and adaptation of CEA (Adeleke et al., 2022; Gathaara et al., 2008). Consumer scepticism towards CEA has been attributed to a lack of familiarity and experience (Adeleke et al., 2022), perceived high energy consumption during production, mistrust of innovative technologies (Gathaara et al., 2008) and anticipated high cost of food (Bukachi et al., 2021). Other studies have demonstrated a more favourable attitude towards CEA and alternative FPS (e.g. van Gorcum et al., 2019; Wascher et al., 2015). Specifically, hotels, restaurants, and retailers expressed a positive perception of aquaponics despite a lack of familiarity with the concept. These stakeholders have also exhibited a willingness to pay a premium for aquaponic products (van Gorcum et al., 2019).

4.2.3 Infrastructure in Nairobi

An advantageous aspect of implementing CEA in Nairobi is the availability of shipping containers, which can be repurposed to integrate CEA (IN_03). Neruva, a start-up situated 33 km away from Nairobi's central business district, has employed a 40-foot shipping container to incorporate an aquaponics system. The enterprise intends to bring food production closer to the customer (Ngige, 2022). While Nairobi hosts a diverse range of 77 agri-tech start-ups, only Neruva was identified as currently involved in CEA. The other agri-tech start-ups offer supplementary online marketplaces to educate farmers about the prevailing market prices or software aimed at improving agricultural supply chain management with farmers, transportation, and vendors (Tracxn, 2023).

However, challenges related to infrastructure for the implementation of CEA in Nairobi include (see Supplementary Material F):

- The lack of space (IN_02, IN_05, IN_08, IN_09, IN_10, IN_11, IN_12, IN_15, Waithanji et al., 2020),
- High land rents (Waithanji et al., 2020),
- The high cost of the technology itself,
- The challenge to find potential investors (IN_01, IN_03, IN_07, IN_08, IN_10, IN_11),
- Lack of skilled workforces to operate urban CEA (IN_02, IN_10, Ozor et al., 2021; Waithanji et al., 2020),
- The scarcity of water resources and
- The high expense for electricity (IN_01, IN_02, IN_03, IN_10, IN_14).

The reliability of the electricity power supply is precarious, which can result in prolonged blackouts (IN_14). Furthermore, the utilisation of delicate technologies entails the threat of theft, as the components can be sold for financial gain (IN_06, IN_14).

4.3 Singapore

4.3.1 Actor constellation in Singapore

Singapore has a well-developed IS for urban CEA. Its implementation is supported by actors from the public sector, knowledge institutions, VCA and the private sector (see Table 3 and Supplementary Material B).

Public sector actors are crucial in enabling urban CEA due to their role in creating a supportive regulatory and policy framework through legislation, policies, guidelines, green and building standards. A key actor here is the Singapore Food Agency (SFA), which has launched a number of programmes and guidelines for urban CEA (IS_04, IS_05, IS_07, IS_08, Wood et al., 2020). Furthermore, the SFA provides funding initiatives to enable urban CEA (Mok et al., 2020; Wood et al., 2020; Yoon et al., 2021) and leases urban land for various purposes (IS_03, IS_05, IS_06, IS_11):

> *"[…] land is owned by the government, the SLA, Singapore Land Authority […]. There's very little private land in Singapore. The majority, most of it, is owned by the government, so everything is leasehold. So, any building is leasehold. […] if you wanted to do, like, a rooftop, you would have to lease from the building management" (IS_05: 206-210).*

Additionally, the SFA fosters partnerships with local CEA entrepreneurs (Yoon et al., 2021). They also provide training to support the implementation of urban CEA initiatives (Wood et al., 2020). Due to their monitoring role in waste and water discharges, as well as fire safety aspects (IS_03, IS_04, IS_11), public sector actors ought to play an important role in implementing urban CEA (IS_07, IS_09).

Other relevant actors for implementing CEA in Singapore include VCA (e.g. entrepreneurs, consumers, retailers) who adopt CEA and purchase CEA products

Table 3 Relevant actor groups and perceived roles for implementing CEA in Singapore

Actor group	Reported functions related to the implementation of CEA
Public sector actors	• Establishing a supportive regulatory framework • Providing high investments in CEA • Leasing urban land • Offering rooftops for installing CEA • Facilitating partnerships with local entrepreneurs • Offering training programmes • Supporting the implementation of CEA projects • Monitoring waste and water discharges • Ensuring fire safety measures are in place • Fostering partnerships with local stakeholders
Value chain actors	• Selling and buying CEA products • Adopting CEA
Knowledge institutes	• Conducting R&D • Sharing knowledge to assist in the implementation of CEA • Networking of CEA entrepreneurs and other researchers
Private sector	• Providing consultancy to UA initiatives • Offering private investment in the R&D of CEA • Adopting CEA

Source: Author's compilation (2023) based on the expert interviews (n = 11) and Diehl et al. (2019), Mok et al. (2020), Wood et al. (2020) and Yoon et al. (2021)

(Mok et al., 2020, IS_04, IS_06-IS_08, IS_11), as well as knowledge institutions conducting R&D (IS_06, IS_11, Mok et al., 2020; Wood et al., 2020; Yoon et al., 2021). Additionally, the private sector provides consulting services and offers private investments for CEA initiatives (Wood et al., 2020).

4.3.2 Institutional framework in Singapore

Formal institutions in Singapore Singapore features a well-developed and well-aligned institutional environment for urban CEA (see Supplementary Material E). As part of the *C40 Cities Food System Network*, Singapore strives to establish a food system that is both healthy and accessible while concurrently reducing food loss and waste (C40 Cities Climate Leadership Group, 2022). The main strategy for implementing CEA in Singapore is the *'30 by 30' strategy* (Singapore Food Agency, 2023), which sets out to enhance local production to meet 30% of the country's nutritional needs by 2030 (IS_01, IS_02, IS_10, Teng, 2020; Wood et al., 2020). In this context, significant investments in R&D facilitate the creation and implementation of innovative FPS, with particular emphasis placed on advanced technologies (e.g. VF, container farming) and novel food solutions (e.g. alternative protein sources) (Diehl et al., 2019; Kosorić et al., 2019; Teng, 2020). In particular, the *Agri-Food Cluster Transformation Fund* has granted $23 million for R&D in sustainable UFP (SFA, 2022). The *30 × 30 Express* grant provided $30 million to aid the agri-food sector to enhance local food production (SFA, 2020).

Numerous programmes in Singapore endorse the development of urban CEA, including the *Singapore Food Security Roadmap* that has been launched in 2013 to establish guidelines for optimising local food production (Da Wei & Hong, 2019). According to the interviewees, laws and regulations that may be pertinent to the application of CEA are connected to food safety concerns (IS_03, IS_06, IS_07, IS_10, IS_11). Nonetheless, establishing CEA requires compliance with numerous regulatory requirements (e.g. building codes, fire safety standards), which entails high levels of bureaucracy and administration (IS_03, IS_08, IS_10, IS_11, Fu, 2020). Furthermore, the deployment of CEA in urban areas is subject to rigorous control under land use zoning standards (IS_03, IS_06, IS_11, Fu, 2020).

To safeguard new developments in food production or technical advancements, Singapore provides a diverse range of IP protection, such as patents, trademarks, copyrights and trade secrets. The Intellectual Property Office of Singapore was created to oversee and secure the IP assets of companies (Medina, 2023).

Informal institutions in Singapore Singapore's formal institutions play an important role in shaping the informal institutions that influence the food culture of Singapore. The background is an elitist and meritocratic political system with a highly-educated and well-paid public service (Bellows, 2009), very low levels of corruption (Transparency International, 2022) and ostensive pragmatism as the dominant social norm (Yeo, 2010). However, the meritocratic narrative also normalises elements of discrimination in a multiracial society (Teo, 2019). Good governance is prioritised over competitive democracy (Yeo, 2010). Despite

formal democratic institutions, the ruling People's Action Party (PAP) has established political dominance since independence in 1959 and the resulting political system has been characterised as "networked autocracy" (George, 2009).

State-led initiatives to create a national identity in a multiracial society have also influenced the food culture in Singapore (Duffy & Hui Xian, 2021). Singapore embraces a narrative of being a country of food lovers with a strong community spirit and emphasis on family values (Duffy & Hui Xian, 2021; Ferzacca et al., 2013). Singapore's gastronomy caters to diverse dietary preferences with the aim of boosting international tourism, building on the inclusion of different cultural traditions (under the umbrella terms Chinese, Malaysian and Indian) in Singapore's cuisine (Duffy & Hui Xian, 2021). Although insects are used as feed in Singapore, the mere notion of ingesting insects is met with resistance by the population (IS_01, IS_03, IS_05, IS_06).

Our interviewees reported that in response to the Covid-19 pandemic, Singaporean consumers have demonstrated a growing concern about the sources of food (IS_01, IS_04) and a preference for locally grown food (IS_05, IS_09). Their primary concern is that the food they consume is safe, fresh, healthy and hygienic (IS_02, IS_03, IS_07, IS_10). Consumers in Singapore associate CEA with controlled growing conditions, where fresh and safe food can be produced locally (Ares et al., 2021). However, the high price sensitivity of Singaporeans poses a potential disadvantage for CEA. If CEA products are more expensive at the point of sale in comparison to imported food, the overall uptake of CEA may be limited (IS_03, IS_04, IS_10, Ares et al., 2021; Gastón et al., 2021):

> *"And also, our consumers are a little bit price sensitive. They won't buy more, they won't pay more just because it is organic. They go for what is affordable. If you have a certain discount, they will go for it. So they are price sensitive" (IS_04: 155ff.).*

One participant noted an increase in the number of restaurants offering vegetarian, vegan, or meat alternative dishes (IS_05). Evidence suggests that Singaporeans, especially the younger generation, have relatively positive *behaviours and attitudes* towards urban CEA (IS_01, IS_02, IS_ 04-IS_07, IS_09, Ares et al., 2021; Gastón et al., 2021; Kosorić et al., 2019):

> *"And there's a definite demographic preference for outdoor grown vegetables versus vegetables grown under novel systems. The younger consumers, the millennials seem to accept indoor vegetables much more than over 50 years old, older generations of the demographic. They still prefer to have more natural food" (IS_03: 312ff.).*

4.3.3 Infrastructure in Singapore

The Singapore government has introduced the *Singapore Food Bowl* programme with the intention of developing a more resilient, sustainable, and decentralised agrifood system in response to the COVID-19 pandemic. The programme engages agrifood tech start-ups from Singapore and across the Asia-Pacific region to achieve this objective (AFN, 2020). Singapore boasts its political support and investment in R&D, aspiring to be a prime "[…] innovation hub for corporate partnerships and venture ecosystems to develop and distribute urban food systems for the wider pan-Asian area" (Kulasooriya & Manogaran, 2021: 11). The city aims to attract start-ups and corporations in the areas of innovative FPS and alternative protein sources (Kulasooriya & Manogaran, 2021).

However, there are also some infrastructural barriers to the implementation of CEA in Singapore (see Supplementary Material F). The main obstacles reported are:

- Lack of space to implement CEA on a large scale (IS_02, IS_04, IS_05, IS_07, IS_10, Mok et al., 2020; Wood et al., 2020),
- The high costs of land (IS_02, IS_10) and natural resources (e.g. water and electricity) (IS_02, He & Lee, 2013; Mok et al., 2020),
- The high cost of the technology itself (IS_05, IS_07, IS_08, IS_10, IS_11),
- The high costs of obtaining a licence (IS_05, IS_07, IS_08, IS_10, IS_11),
- The lack of knowledge, skills and available manpower to operate CEA (IS_02, IS_05, IS_06, IS_07, IS_08, Wood et al., 2020) and
- The risk of cyber-attacks (IS_04, Wood et al., 2020).

5 Discussion

Our analysis of the UFoPrInS in the three cases unveiled commonalities and differences in their structural strengths and weaknesses. These are summarised in Table 4.

The structural strengths and weaknesses of the three UFoPrInS reflect their ability to provide conditions for the successful development and implementation of urban CEA. In this section we discuss to what degree the strengths and weaknesses correspond to the advantages of CEA and challenges for their development and implementation that have been defined in the literature. Benke and Tomkins (2017) highlight benefits in resource efficiency and independence of production from seasons and weather events, which translate into possible economic, ecological, social and political advantages. They also identify eight main challenges of CEA: high start-up costs, high energy consumption and

Table 4 Structural strengths and weaknesses of the UFoPrInS in London, Nairobi and Singapore

	Structural dimensions	**Commonalities of London, Nairobi and Singapore**		
Structural strengths	Presence and capabilities of actors	Various actors are relevant in the implementation of urban CEA. Key role of public sector as initiator and enabler.		
	Institutional environment	Internationally harmonised IP rights are available to protect innovations and technical improvements		
		Recognition of CEA in local food strategies as an option for pathway for food production		
		Increasing consumer demand for local, organic, healthy, vegetarian and vegan products		
		General acceptance of insects as feed		
	Infrastructure	Variety of knowledge institutions, established corporations and agri-tech start-ups		
Structural weaknesses	Presence and capabilities of actors	Scarcity of trained workforce to operate CEA		
	Institutional environment	Many price sensitive consumers and budget-constrained households		
		General rejection of insects as food		
	Infrastructure	Food insecurity affecting some of the local population is a consequence of poverty.		
		Scarcity of and strong competition for urban space		
		High costs for land, natural resources and the technology itself		
		Scarcity of local resources, in particular clean water		
		Lack of tailored training programmes on CEA		
		Lack of private and venture capital		
	Structural dimensions	**Differences**		
		London	*Nairobi*	*Singapore*
Structural strengths	Interactions	Variety of networks promoting different forms of UA, including CEA; networking activities encouraged by the London Food Strategy	Network development driven by research institutes (Mazingira Institute)	Strong collaboration between state and business elites
		High level of CSOs interaction on UA-related issues	High level of NGO interactions on food-related issues	Significant collaboration between public and private sector actors, businesses and knowledge institutions
	Institutional environment	The London Food Strategy promotes UA activities to address food related issues such as child obesity or food insecurity	Nairobi's food strategy promotes UA in order to address food related issues	Ambitious government strategies for CEA; government-sponsored guidance through complex regulatory system and support for networks
		Food-related strategies with the potential to transform the UK food system	UA activities formally recognised as a legitimate form of land use in different policies	Ample public funding opportunities for CEA
		CEA explicitly mentioned in the "Future of Food 2040" report	CEA recognised as a possibility to improve food security and reduce post-harvest losses	Positive public attitudes towards high-tech FPS

Table 4 (continued)

	Presence and capabilities of actors	Actors mainly involved in UA activities		
Structural weaknesses	Institutional environment	Fragmented regulatory and governance structures; institutional gaps and uncertainty in the aftermath of Brexit	Fragmented and partly contradictory regulatory framework	Strict and complex regulatory and planning environment
		No national funding specifically for CEA		High investment in novel food (e.g. alternative proteins)
		Prevailing scepticism in society towards unnatural food production		
	Infrastructure	Unclear and lack of long-term land tenure	Complicated and partly contradictory land tenure and land use system	Restrictive land use zoning standards
		High food import dependency		High food import dependency
			Security risks for valuable components	Risk of cyber attacks

Source: Authors' compilation (2023)

costs, limited number of crop types, production volume and scaling-up, availability of venture capital, disruption to the rural sector, realisation of transportation savings, availability of a skilled workforce for new jobs, and the focus on clean, green, and gourmet (CGG) food.

Starting with the *common structural strengths* of the three UFoPrInS, the key role of public sector actors reflects the expected public benefits from urban CEA, such as increased resilience of local food systems or reduced GHG emissions and environmental footprint, which justify public support and the inclusion of CEA in urban food strategies. Public support is also needed to overcome the lack of competitiveness of current CEA operation on urban land markets, in the labour market and the final product markets, where CEA have to compete with incumbent producers that have depreciated their capital investments. The increasing consumer demand for local, organic, healthy, vegetarian and vegan products encourages CEA's potential to produce "CGG food" (Benke & Tomkins, 2017). General acceptance of insects as feed, pending legal authorisation, enables insect production as a lone-standing enterprise or as part of circular production systems. Strong and internationally harmonised IP rights facilitate the access to the latest technology developments in areas such as LED, energy supply and plant nutrition, which must be combined to create efficient CEA operations.

Some *common structural weaknesses* are related to issues that CEA aims to address. This includes high dependency on imported food and lack of local resources, in particular clean water. CEA proponents promise enhanced resilience of UFP through local food production, and high resource efficiency, in particular water, soil and nutrients. Other common structural weaknesses indicate that the UFoPrInS in our three case studies are struggling to address the challenges identified in previous research. Scarcity of and strong competition for urban space and natural resources such as water often translate into high costs for land and natural resources. This either leads to CEA being located in less densely used areas, or not being realised at all due to lack of competitiveness with established agricultural production. The relatively high costs of the technological components and the scarcity of trained workforce to operate CEA create further market entry barriers for CEA. Uncertain profitability in turn leads to the reported lack of investors and private capital. The prevalence of price-sensitive consumers and budget-constrained households, combined with the relatively small scale of most CEA production which prevents the economies of scale known from the conventional agricultural sector, implies that investors must target high-end CGG markets to present plausible business models. As a consequence, CEA is unlikely to reduce food insecurity caused by low household income and poverty.

The *case-specific strengths* of the three UFoPrInS in our study point towards local conditions that enable the realisation of CEA benefits and help to overcome challenges. All three cities feature lively networks around UA which also include initiatives with an interest in CEA. Such networks can create general support in the community, enhance trust, and lobby for political support. In all three cities, local food strategies translate the societal interest into more institutionalised forms of cooperation, including political and administrative action. The findings from Singapore indicate a high level of institutionalisation with ambitious government strategies and ample funding that facilitates collaboration between public and private sector actors, businesses and knowledge institutions and supports training in CEA-related skills. However, in comparison, the findings from London and Nairobi point towards more bottom-up initiatives with an interest in various forms of UA that reflect the values and ideas of different parts of civil society and private sector.

In contrast, the case-specific *weaknesses* show constraints faced by CEA. Interviewees in London and Nairobi often complained about weak institutionalisation, fragmented networks and policies, a contradictory regulatory framework and a lack of coordination. They also found training in CEA-related skills lacking, despite occasional initiatives. In all three cities, CEA operations must be fitted into often strict urban planning and zoning frameworks. Regarding market structures, a dominance of price-sensitive or poor consumers creates pressure to develop CEA that cater for high-end CGG markets. Many wealthy customers, however, articulate scepticism towards 'unnatural food' and a high willingness to pay must first be created through convincing and credible benefits. These constraints lead to a lack of clear business models, which in turn helps to explain the lack of private investments and venture capital. Additional risks emerge from possible theft of valuable equipment and cyber attacks that threaten the automated monitoring, control and steering systems of CEA operations.

Overall, the findings confirm many of the established challenges to CEA. They also help to understand how they are partly rooted in structural weaknesses of CEA innovation systems. In contrast, structural strengths of UFoPrIns can help to overcome these challenges by facilitating access to knowledge and financial resources, political and public support. However, even with a very strong IS, CEA faces considerable economic hurdles due to high start-up costs, lack of available capital, constraints to scaling-up and lack of skilled labour for new jobs. At the same time, the advantages from a controlled production environment and resource efficiency are not easily translated into viable business models. The three cases suggest that public support and funding are necessary to overcome the competitive advantages of incumbent food production systems which have long co-evolved with the regulatory and policy framework, work with depreciated investments and which have shaped consumer expectations for a long time.

6 Conclusion

Concerns about the sustainability and resilience of urban food systems have led to calls for innovative food production methods capable of providing high-quality, sustainable and healthy food to growing urban populations while strengthening the resilience of food systems. Controlled-environment agriculture (CEA) in urban areas has been proposed as a pathway towards solutions with multiple economic, ecological, social and political benefits (e.g. Beacham et al., 2019; Benke & Tomkins, 2017; Khan et al., 2021). However, many CEA solutions are still in a conceptual or experimental stage. Their implementation, whether in urban or non-urban locations, requires strong innovation systems (IS). This paper therefore adopted an IS perspective (e.g. Edquist, 1997; Lundvall, 1992) to analyse and assess structural strengths and weaknesses of urban food production innovation systems (UFoPrInS) in three selected cities, treating London, Nairobi and Singapore as contrasting cases.

While CEA innovations in Singapore are strongly supported by public policy and funding to enhance the resilience of food supply, London and Nairobi displayed more fragmented network interaction and less aligned political and regulatory frameworks. In London, CEA implementation has been held back by other policy priorities, infrastructure constraints and high costs of urban space. In Nairobi, CEA lacks political support unless it can plausibly help to tackle food insecurity caused by poverty. Currently, low-tech urban and rural agriculture, reducing yield gaps and adapting agricultural production to climate change are probably more adapted and efficient strategies to enhance food security.

In all three cases, lack of available urban space, high energy costs, lack of specifically trained labour and scarcity of private capital remain significant obstacles to the development, implementation and diffusion of CEA innovations. While rural locations might offer lower costs of land and space, they typically create greater challenges regarding the availability of skilled labour, market access, and linkages to knowledge institutions. To create additional value from their urban location, some CEA have turned to creating additional value by creating links to tourism and hospitality. On the production side, a focus on high-end markets for clean, green, and gourmet (CGG) food is likely. Both developments direct the development of CEA towards applications that cater to wealthy consumers rather than to hungry households.

As CEA mostly comprises capital- and knowledge-intensive, resource- and space-saving production systems that enable food production even in naturally and climatically less suitable locations, their implementation could be particularly suitable in locations where capital and knowledge are abundant, stable political, social and infrastructural conditions prevail, where resources and space are scarce and where local production of fresh food is not possible with traditional agricultural methods. However,

under current price relations, material efficiency and the closing of material cycles often do not translate into economic and monetary benefits. Higher costs for water and energy and the internalisation of external costs of food production, e.g. through carbon pricing (Reimers et al., 2021; Sgarciu et al., 2023), would reward resource efficiency gains. This would encourage more actors to seek resource-efficient solutions in food production, thereby stimulating interest in CEA solutions. Expanding networks would facilitate initiatives to develop knowledge and improve skills, build absorptive capacity and create critical mass for innovation (Cohen & Levinthal, 1990; Lundvall, 1992). Increased networking activities can also reduce transaction costs, foster partnerships or stimulate learning (Powell & Grodal, 2006; Rutten & Boekema, 2013) and ultimately strengthen the performance of an IS. Networking could be facilitated by platforms, public-private partnerships (Klerkx et al., 2012) or increased public and private funding (Klerkx & Leeuwis, 2009; Paredes-Frigolett & Pyka, 2017). Hence, the direction of search in CEA innovations will be strongly guided by broader economic and regulatory frameworks that determine the availability and relative price of natural resources, eco-system services and emission entitlements.

Methodologically, the IS approach proved useful in identifying the structural characteristics of UFoPrInS and the factors that influence the implementation of CEA in urban areas. By examining the structural dimensions of such IS (actors, their networks, the existing institutional framework, available resources, infrastructure conditions and local residents), it was possible to identify elements of UFoPrInS that support or constrain the implementation of CEA in urban locations. While the findings generally confirm established advantages and challenges of CEA, they also help to better explain the contextual factors that alleviate or reinforce the challenges and that enable or constrain the realisation of the potential benefits of CEA. At the same time, the results suggest that narratives which present urban CEA as an immediate solution to overcome food insecurity are not well aligned with the technological and economic characteristics of most CEA concepts. The analysis also calls into question generic calls for public support for the implementation and operation of CEA. Instead, the reasons for public support for CEA beyond the research and development stage require careful elaboration and critical examination.

Future research should complement the structural analysis of different UFoPrInS with a functional analysis (Bergek et al., 2008; Hekkert et al., 2007). A systematic analysis of UFoPrInS helps to understand where, when and why different systemic problems occur in the innovation process. This systematic analysis can form the basis for developing policy recommendations to address systemic problems in the innovation process and improve the capacity of UFoPrInS to implement urban CEFPS (Hekkert et al., 2020; Wesseling & Meijerhof, 2023). Furthermore, a better understanding of the business models linked to CEA for different urban contexts must be developed to identify eventual reasons for public intervention. Moreover, a survey with the local population and consumers could help to gain insights on their attitudes towards and acceptance of CEA. Given the different structural weaknesses of the three UFoPrInS analysed in this paper, an important question is how CEA could be technically adapted to the specific contexts, e.g. in terms of frugal innovation (Zeschky et al., 2011), while still following the principles of resource efficiency.

Appendices

Appendix A

Table 5 lists the acronyms used in this paper.

Table 5 Acronyms used and explanations

Acronym	Explanation	Reference
CEA	Controlled-environment agriculture	Benke and Tomkins (2017)
UFoPrInS	Urban Food Production Innovation System	Dietze and Feindt (2023)
EU	European Union	Established abbreviation
UK	United Kingdom	Established abbreviation
IS	Innovation system	Edquist (1997)
UFP	Urban food production	own abbreviation
ELMS	Environmental Land Management Scheme	Kendall (2020)
IP	Intellectual Property	Established abbreviation
CSO	Civil society organisation	Established abbreviation
VCA	Value chain actors	Established abbreviation
VF	Vertical farming	Beacham et al. (2019)
IoT	Internet of Things	Khan et al. (2021)
UA	Urban Agriculture	Marini et al. (2023)
LCA	Life cycle assessment	Srinivasan and Yadav (2023)
CEA IS	Controlled-environment agriculture innovation system	Own abbreviation

Source: Authors' compilation (2023)

Appendix B

Table 6 contains the deductive codes we created to systematically analyse the relevant documents.

Table 6 Deductive codes for qualitative content analysis

Topic	Codes
Actor constellation	• Knowledge institutes • Actors in urban settings • Civil society organisations • Value chain actors • Private sector • Public sector actors (e.g. political actors, administration, media, schools)
Formal institutions	• Laws and regulations • Funding institutions • Statutory requirements
Informal institutions	• Habits • Values and norms • Behaviours and attitudes • Cultural context • Religious aspects
Infrastructure	• Physical resources • Natural resources • Financial resources

Source: Authors' compilation (2023) based on Coenen and Díaz López (2009), Edquist and Johnson (1997), North (1991), Saxena et al. (1990), Sosik et al. (2005), Termeer et al. (2019), Wenzelburger and Zohlnhöfer (2014)

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Declarations

Ethical declaration Participants gave informed consent and their anonymity is assured.

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