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PAPER

Qualitative analysis of hydroponic container farm adoption, use, and benefits in the U.S.

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Abstract

The impacts of climate change, population growth, and resource constraints on conventional agriculture have sparked interest in controlled environment agriculture (CEA) technology. The hydroponic container farm (HCF) is a type of small-scale CEA infrastructure increasingly being adopted by cities, businesses, and nonprofits. Yet there is still significant uncertainty about HCF use, potential value to the food system, and broader sustainability benefits and tradeoffs. This research uses semi-structured interviews with farmers operating HCFs across the U.S. and grounded theory analysis to characterize HCF use, outcomes, benefits, and challenges. Results show that HCFs contribute direct benefits as food system infrastructure through food production, particularly in urban regions where conventional agriculture is infeasible, but also provide indirect benefits through education, workforce development, and broader social impact. Despite wide differences in the ways organizations use HCFs, we identified universal factors that moderate successful outcomes, including municipal zoning and permitting regulations, relationships between the HCF farmer and partners, the business model under which the HCF operates, and the design and cost of hydroponic technology. This study begins to characterize the social and economic tradeoffs that HCFs generate and provides use case data for future quantifications of environmental impact.

1. Introduction

The world's population is expected to reach 9.77 billion people by 2050 (UN DESA 2019)—over two thirds of whom are expected to live in cities (UN DESA 2019)—leading to a projected increase in food demand of over 60% from 2010 levels (van Dijk *et al* 2021). Urban food systems already grapple with inequitable access to healthy foods (Losada-Rojas *et al* 2021), and urban populations often face persistent food insecurity (Hecht *et al* 2019, Coleman-Jensen *et al* 2022). Urbanization is also associated with increased consumption of processed and pre-prepared foods (Satterthwaite *et al* 2010) and decreased consumer understanding of and engagement with food production (Turner 2011).

Meeting this growing demand with food produced by conventional agriculture will exacerbate environmental impacts, including water pollution and eutrophication (Pimentel *et al* 2005, Parris 2011), land use change and habitat destruction (Mbow *et al* 2019), and greenhouse gas emissions (Neue 1993, Mbow *et al* 2019, Shakoor *et al* 2021) associated with food production (Costello *et al* 2015, Romeiko *et al* 2020). The agricultural sector contributed 22% of global anthropogenic greenhouse gas emissions in 2019 (IPCC 2022), and yet is vulnerable to global climate impacts, including extreme heat, heavy precipitation, and drought (Arias *et al* 2021), and the associated decline in yields from extreme weather events, water shortage, and pest and disease distribution (Agovino *et al* 2019, Gruda *et al* 2019, Mbow *et al* 2019).

Addressing the complex sustainability challenges of conventional food systems will require innovative solutions in how food is grown and distributed. One such innovation is controlled environment agriculture (CEA) (Cetegen and Stuber 2021, Saad *et al* 2021, Ojo and Zahid 2022). Broadly, CEA includes agricultural production techniques that combine plant science, engineering, and environmental control to optimize efficiency and plant growth (Shamshiri *et al* 2018). Simple CEA infrastructure, including greenhouses and cold frames, has been used for centuries, but as technology advanced in recent decades, so has the size, scale, and modularity of modern systems. Since the publication of *The Vertical Farm* in 2010 (Despommier 2010), interest in indoor, vertical, urban CEA has increased markedly (Cetegen and Stuber 2021). This sector now includes high-tech methods with potential advantages for urban food production, including vertical farming, indoor growing, and soilless growing techniques like hydroponics, aeroponics, and aquaponics.

CEA offers an environment that is more resistant to insects, extreme precipitation, and high wind speeds (Shamshiri *et al* 2018, Gruda *et al* 2019), while requiring less water to grow crops than conventional farming methods (Barbosa *et al* 2015, Van Ginkel *et al* 2017, Verdoliva *et al* 2021). Use of environmental control systems also enable farms to operate independently from outside environmental conditions, meaning they can be located in areas where conventional agriculture is not viable, like urban centers (Wu *et al* 2019) and regions with harsh climates (McCartney and Lefsrud 2018). By locating food production closer to major consumption points like urban centers, the complex food supply chain and associated storage dynamics and transport costs (Wang *et al* 2023) can be simplified, and the carbon emissions from refrigerated food transportation (Wang *et al* 2022) can be reduced. CEA also has the potential to positively impact the local community by providing year-round crop production, job creation, opportunities for social communication and leisure (Benke and Tomkins 2017, Shamshiri *et al* 2018), and access to green space that is associated with increased subjective well-being (Das *et al* 2022).

However, CEA systems also have the potential to create tradeoffs (Srinivasan and Yadav 2023), many of which are not fully understood. Indoor hydroponic systems use more electricity than conventional farms (Barbosa *et al* 2015, Van Ginkel *et al* 2017, Pomoni *et al* 2023) and generate variable carbon emissions depending on farm design and location (Eaton *et al* 2023). While shifting from low- to high-intensity CEA systems can reduce local environmental impacts, they may shift life cycle impacts to a more global scale (Ghamkhar *et al* 2021). From an economic perspective, CEA often comes with high capital investment (Pomoni *et al* 2023) and higher produce landed costs (Nicholson *et al* 2023), and the economic viability of large-scale CEA systems has recently been questioned by agribusiness experts (Gordon-Smith 2023, Pollard 2023). Application of CEA within urban areas can be a profitable way to provide localized food supplies (Gumisiriza *et al* 2022), but in some regions may be limited by the cost of land in central business districts (Benke and Tomkins 2017) and subject to local policies and zoning regulations (Goodman and Minner 2019), which can be a hindrance (Huang and Drescher 2015).

These challenges motivate the need to develop CEA systems that can be sited and operated efficiently to produce food where it can be used by urban populations (Velazquez-Gonzalez *et al* 2022). One type of CEA potentially well-suited for urban production is the hydroponic container farm (HCF), also known as a container farm (Sambor *et al* 2020, Her *et al* 2021, Song *et al* 2023), hydroponic shipping container farm (Wagner *et al* 2021), modified hydroponic shipping container (Sparks and Stwalley 2018), container-sized agricultural unit (Farfan *et al* 2019), grow-cell (Tsitsimpelis and Taylor 2014, Tsitsimpelis *et al* 2016), growing container (Kuang *et al* 2022), or by the manufacturer name 'Freight Farm.' The HCF is a modular, self-contained farm built inside a refurbished shipping container (Square Roots 2022) or a custom-built container with the same dimensions (ZipGrow 2022). The company Freight Farms first began manufacturing HCFs at scale in 2013 (Freight Farms, n.d.-a), and today, there are dozens of companies worldwide that design and produce these turnkey, 'plug-and-play' hydroponic systems.

While HCFs offer potential for flexible urban food production, the economic, social, and environmental implications of their use are unclear. Previous literature has modeled HCF energy use (Sparks and Stwalley 2018, Liebman-Pelaez *et al* 2021), and estimated that vegetables grown in HCFs require 30 times more energy per kilogram than conventionally-grown produce (Van Ginkel *et al* 2017). However, research has also suggested ways to reduce HCF energy consumption and costs by optimizing lighting and climate control systems (Tsitsimpelis *et al* 2016, Kuang *et al* 2022), siting HCFs in colder climates (Song *et al* 2023), or meeting demand using renewable energy sources. For example, in a remote arctic microgrid, HCFs had up to 18% operating cost reduction when coupled with optimized solar energy generation (Sambor *et al* 2020), and could serve as dispatchable load for excess energy from wind turbines (Her *et al* 2021). One estimate suggested that using just 3.6% of the total renewable energy generation projected for 2050 could power enough HCFs to meet 24% of recommended vegetable intake for the world's population (Farfan *et al* 2019).

From an economic perspective, HCFs can be challenging to operate profitably (Sparks and Stwalley 2018, Farfan *et al* 2019, Wagner *et al* 2021, Bafort *et al* 2022). In a survey of 12 HCF operators in the US, half disagreed or strongly disagreed that HCFs were profitable (Wagner *et al* 2021). While high-value crops have the most revenue potential (Sparks and Stwalley 2018), profits may be eroded when businesses experience steep learning curves, high operating costs, low yields, and lack of support from HCF manufacturers (Wagner *et al* 2021). However, existing studies have largely focused on for-profit businesses, and it is not clear if similar challenges exist for other organizations operating HCFs. Additionally, no study has yet investigated the social dimensions of adopting and operating HCFs.

To evaluate the social, economic, and environmental benefits and tradeoffs of HCFs within the food system, we need a clearer understanding of how they are being used, by whom, and for what purpose. Therefore, this study aims to characterize the current use of HCFs in the U.S. and evaluate HCF benefits and challenges from the perspectives of owners and operators. The research assesses three main aspects of HCF use: (1) why and for what purposes HCFs are being adopted, (2) how HCFs are being used and to what extent they meet users' needs, and (3) overall opinions, perspectives, and lessons learned from operating an HCF. These findings can then be used to evaluate the potential role HCFs can play in building a more resilient and sustainable food system, and help inform future analyses of profitability and environmental impact for a wide array of use cases.

2. Methods

To explore HCF adoption in the U.S. food system, this study uses qualitative methods including semi-structured interviewing and grounded theory analysis. Qualitative methods have been useful for studying aspects of sustainable agriculture, including climate-resilient behaviors (Niles *et al* 2016, Juhola *et al* 2017) and barriers to adopting sustainable technology (Long *et al* 2016a). Grounded theory in particular is well-suited to exploring complex social situations and experiences (Corbin and Strauss 2008), such as decision-making around synthetic pesticide use (López de Mesa 2020) and the performance and sustainability of farm cooperatives (Yu *et al* 2023). Here, we use a grounded theory approach to systematically gather and analyze data regarding decision-making, experiences, and opinions of those operating HCFs to explore the challenges and opportunities this technology presents.

2.1. Grounded theory framework

Grounded theory methodology is applied to create conceptual theories 'grounded' in data without imposition of preconceived hypotheses (Glaser and Strauss 1965, 1967). Its advantages in analyzing the experiences and motivations of individuals (Charmaz 2006, O'Connor and Joffe 2020) make this method suitable for the case of HCF use, given the limited data about why such systems are being adopted, how they are used in practice, and whether they contribute to food system sustainability. In particular, we follow constructivist grounded theory, which positions the researcher in an active role of constructing meaning from the data (Charmaz 2000, 2006, Mills *et al* 2006).

An overview of sampling, data collection, and analysis is summarized in figure 1. In brief, sampling and data collection included theoretical sampling, semi-structured interviews, and interview transcription. Interview data were analyzed through qualitative grounded theory analysis, including three stages of coding conducted iteratively along with interviews and memo-writing to explore the development of codes and relationships between them. The culmination of this analysis was development of a theoretical framework that describes HCF use in the U.S. Further details about the methods are described in the following sections.

2.2. Sampling and data collection

Prior to data collection, study and interview protocols were approved by the Rochester Institute of Technology Institutional Review Board. This study recruited U.S.-based adult interview subjects with direct knowledge of and experience with HCF use. Potential subjects were identified through web searches combining the names of HCF manufacturing companies with terms 'customers,' 'users,' 'farms,' 'news,' or 'production.' Manufacturer websites were also searched for case studies, news stories, and other publicly available information about their customers. For all U.S.-based organizations determined to be operating at least one HCF, their websites were reviewed to identify potential subjects likely to have direct knowledge about the HCF (e.g. 'Farm Manager,' 'Manager of Urban Agriculture,' or for some small businesses, 'Owner' or 'Founder'). Snowball sampling was also used to identify additional organizations not revealed through web search.

These search methods identified approximately 100 organizations using HCFs, of which, 60 were selected as potential subjects through theoretical sampling to capture wide variation in organization type, size, and geographic location and, as the interview process went on, to fill knowledge gaps in the developing theory. Potential subjects were contacted via email, with one follow-up email sent a week later if no response was received. The interview solicitation email scripts are available in the supplementary information (S.I.). The interview response rate was 43%. Interviews were conducted via Zoom, Google Meets, or phone call. All

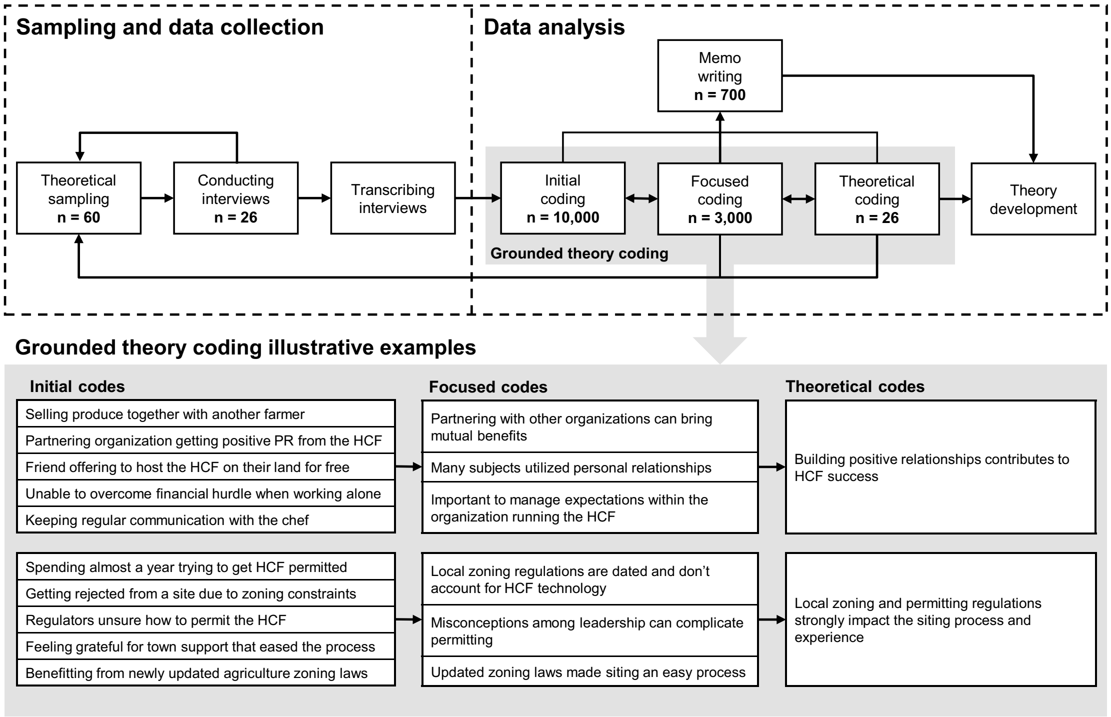

Figure 1. Overview of study sampling and analysis methods. The top box shows the iterative steps of sampling, data collection, and data analysis. The sampling and data collection section shows the number of subjects sampled and interviewed, and the data analysis section shows the number of codes and memos written during each step. The bottom shaded box shows examples of representative initial, focused, and theoretical codes that arose from transcript data to illustrate a portion of the grounded theory coding process.

subjects provided informed consent to be interviewed and gave permission for the researcher to record the conversation. Interviews were conducted between December 2020 and September 2021 in parallel with data analysis. In total, 26 interviews were conducted, lasting between 23 and 70 minutes with a median length of 58 minutes.

The interview protocol (see S.I.) consisted of questions organized in three main categories: (1) considerations and anticipated benefits while deciding to obtain an HCF, (2) characteristics of HCF operation at the organization, and (3) lessons learned, key takeaways, and opinions about overall HCF experience and potential. Questions also explored social, economic, and environmental considerations. The flexibility of the semi-structured format (Kallio *et al* 2016) allowed subjects to speak freely and discuss what they felt were the most important aspects of their experience. Interviews were conducted iteratively throughout data collection and analysis to the point of theoretical saturation, where new interviews ceased to advance theory development.

Interview recordings were transcribed using Zoom's transcription service with manual review and revision by the researchers. Interviews were transcribed verbatim to preserve all data from the subjects. All identifying information was removed from transcripts, and interview materials were anonymized with code numbers. The qualitative data management programs MAXQDA Analytics Pro 2020 and 2022 were used to analyze the anonymized interview transcripts and audio recordings.

2.3. Data analysis

Interview data were analyzed iteratively by grounded theory coding. The first stage was initial coding, where ideas on the order of a single phrase in a transcript were tagged with short descriptions to separate the data into workable components. The second stage was focused coding, where larger segments of data were categorized across multiple transcripts with more selective descriptions that began to show interactions within the data. The third stage was theoretical coding, where overall concepts and relationships were characterized in support of subsequent theory development. Figure 1 highlights representative examples of codes that arose from transcript data during each stage of coding. Overall, about 10 000 initial codes and 3 000 focused codes were assigned to interview transcripts. These codes ultimately formed 26 theoretical codes that described major motivations, processes, benefits, and challenges of obtaining and operating HCFs. S.I. Figures S2 and S3 use a selection of transcript and coding data to illustrate the relationship between these stages in greater detail.

Throughout all stages of coding, memos were written as an additional method of processing data. Early memos clarified and elaborated developing concepts and asked questions about preliminary ideas. As analysis progressed, subsequent theoretical memos captured advanced descriptions of emerging categories and the relationships between them that contributed directly to theory development. About 700 memos were written in total, ranging from brief initial memos, to in-depth analytical descriptions of themes within the data. S.I. Figures S4 and S5 show examples of preliminary and advanced memos from this process.

Intercoder consistency was tested early to assess the quality and independence of the coding process (O'Connor and Joffe 2020). Two transcripts were coded independently by both the primary coder and another researcher familiar with the topic and methodology. Similar themes were identified by both coders with minimal areas of divergence, and intercoder consistency was determined to be sufficient. Subsequent analysis was continued by the primary coder for the remainder of the data.

Theoretical saturation was achieved using constant comparative methods that compared ideas within and between transcripts at all stages of data collection and analysis. From the theoretical codes and advanced memos arose primary categories that together formed a theory about HCF use that is grounded in the interview data (Charmaz 2006). This grounded theory identifies HCF use, benefits, and drawbacks; characterizes the relationship between the HCF's characteristics and the overarching goals of the organization; and describes how the environment in which the HCF operates influences its success. The following sections include the main findings from this theory along with direct quotes from subjects, which have been lightly edited for readability and to preserve anonymity (Lingard 2019).

3. Results

Research findings show both a high degree of variability in how HCFs are being used by different organizations, as well as common practices and challenges in operating HCFs regardless of the nature of use. Collectively, results illustrate varied ways in which HCFs are functioning as food system infrastructure and also contributing to direct and indirect social, economic, and environmental sustainability goals.

3.1. HCF use is highly variable according to the motivations of the operating organization

One of the strongest themes to arise from interviews is that there is no 'one-size fits all' model for how HCFs are currently being used in the food system. There is significant variability in the types of organizations operating HCFs, the organizations' primary motivations and goals, farmers' backgrounds, and locations where HCFs are being deployed.

3.1.1. Characteristics of HCF systems and farmers

Attributes of the 26 organizations interviewed are summarized in figure 2. These organizations were located in 16 U.S. states spanning nine U.S. Department of Agriculture (USDA) plant hardiness zones. Farms were being used to grow a variety of crops: most commonly leafy greens (including lettuce cultivars, chard, and spinach), followed by cruciferous vegetables (including kale, arugula, and radishes), and herbs (including basil and sorrel), respectively. Almost all organizations were operating one to three HCFs, while two groups had more than four farms in use. Most organizations purchased their farm from one of three U.S.-based manufacturing companies, but three organizations used or were building completely custom farms or were using farms retrofitted from their manufacturer's standard design.

The length of time since beginning HCF operation varied widely, with a minimum of four months and a maximum of six years. One organization was still in the process of acquiring their system at the time of the interview. The HCF operators, or 'farmers,' as we refer to them throughout this paper, came from diverse professional backgrounds, including sales, technology, occupational therapy, mental health counseling, and engineering. About ten subjects had done little to no farming before obtaining their HCF, while others had some agricultural experience, ranging from experimenting with CEA at home to formal education or work in agriculture.

3.1.2. Variation in goals for HCF operation

The organizations operating HCFs fell into four broad categories: 13 were for-profit businesses; five were community-based organizations offering vocational, health, education, or therapeutic services; five were colleges and universities; and three were K-12 schools. Further descriptions of the organizations are available in S.I. table S1. Organizations within the same category often had very different goals or purposes for obtaining and using an HCF (figure 3). Interviews revealed four broad goals or desired outcomes for HCF use: food production, social impact, education, and research. Table 1 provides more detail and representative quotes that illustrate farmers' perceptions of the HCF's performance in each of the four roles.

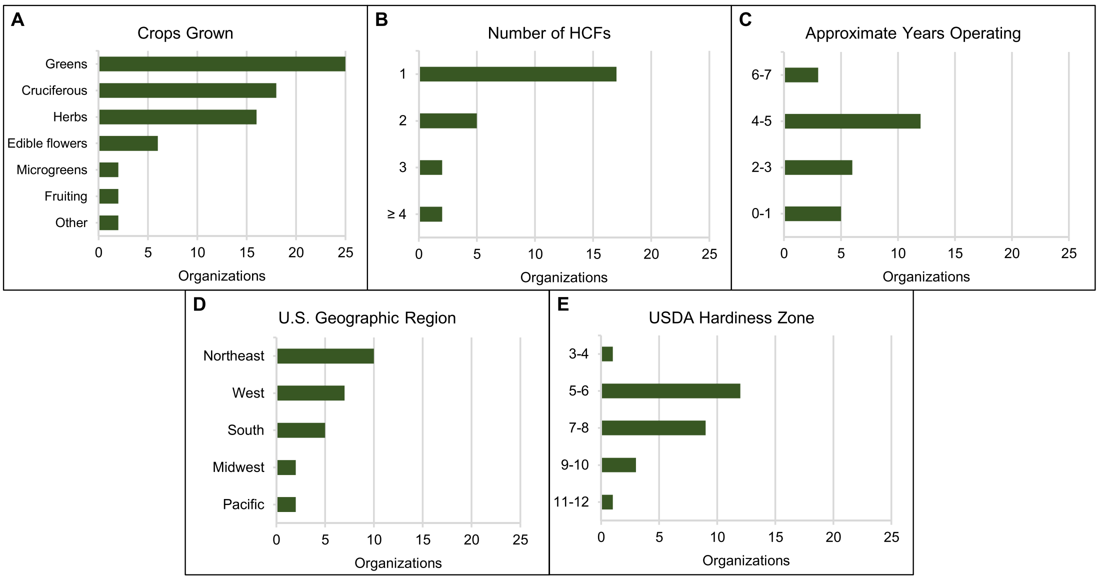

Figure 2. Characteristics of the organizations represented by the 26 interview subjects, including: (A) the types of crops grown (where 'greens' includes leafy greens like lettuce and chard, 'cruciferous' includes vegetables such as kale and arugula, and 'fruiting' includes peppers and strawberries), (B) the number of HCFs each operates, (C) length of time operating their HCF, rounded to the nearest year, (D) the U.S. region and (E) the USDA hardiness zone in which each HCF is located. Data in the 'crops grown' graph sum to greater than 26 because most organizations grow more than one type of crop.

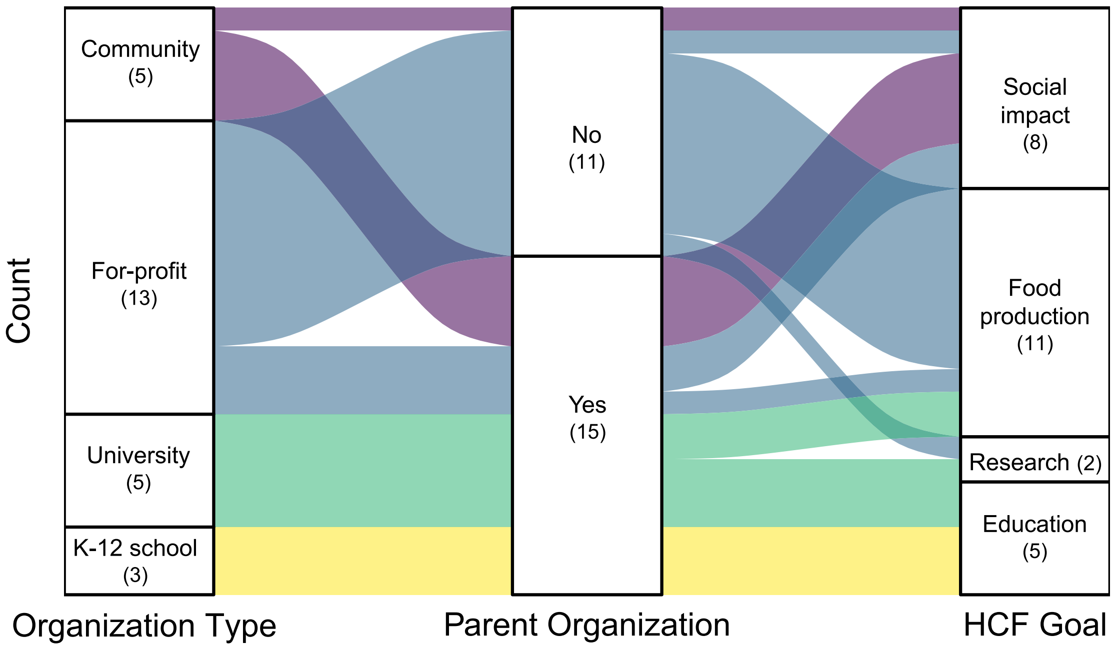

Figure 3. Disaggregation of key characteristics of interview subjects, including the type of organization using the HCF (left), whether or not the HCF operates under a parent organization (center), and the organization's primary goal for HCF operation (right).

The most common goal for the HCF across organizations interviewed was food production ($n = 11$), wherein farmers sought to maximize produce yield and quality and observed specific benefits of using HCFs, including the quality and variety of crops grown and high yield predictability due to the fully controlled environment. In one farmer's description of their produce: 'it's by far the best of anything that I could buy, it really is.' Of the organizations in this category, the majority ($n = 9$) were for-profit businesses selling produce to generate a revenue stream, while two were colleges or universities growing produce to serve at campus dining locations.

Table 1. The four primary goals for HCF operation, as well as perceived benefits that the HCF provides while acting in each role, according to interview subjects. Example quotes from farmers operating their HCFs with each of these four primary goals are provided to illustrate the perceived benefits.

HCF Goal	Perceived benefits relative to goal	Representative quotes
Food production	• Produces high-quality crops • Customers enjoy buying local produce • Capable of growing a wide variety of crops: farmers can establish a niche in the market • Predictable yields enable accurate long-term planning	• 'My customers love it. They say it's the best stuff that they've had.' • 'The ability for [customers] to talk to me, their farmer, directly and know where their food comes from is a huge piece of all of this… I think people like that just as much as they like the food itself.' • 'We can project way out into the future what [crops] we're going to have available, even better than we could in greenhouses.'
Social impact	• Can engage and educate community members • Serves as a platform for job skills training or mental health counseling • Provides purposeful employment and a positive work environment • Repetitive tasks in the HCF are good for some with disabilities	• 'This is more about the social cause of providing jobs than [it] is growing plants.' • '[Farming is] such a good analogy for mental health: you learn what works and what doesn't, and then you learn from that mistake or that success.' • '[Working in the HCF is] the same thing every week. So, it teaches [clients] to follow a schedule and follow a list of duties, like on a job.'
Education	• Helps teach students where food comes from • Encourages children to enjoy vegetables • Students involved in farming develop soft skills • Can connect to a wide variety of classes and coursework • Can inspire the formation of new courses	• 'Making that connection between planting a seed and then eating the food… that experience is something that too many people don't have.' • 'There's been a lot of feedback from the parents that they're seeing their kids… enjoy eating salads and greens and they're being healthier.' • '[Students] learn to be independent in the space. They learn teamwork, they learn a lot of soft skills… specifically through the farm.'
Research	• Acts as a platform to learn about the CEA industry, with the potential to project experiences to other CEA endeavors • HCF is a fast, low-cost, single-farmer option to get started in the CEA industry • Can enable student research and work experiences	• 'The idea was not to not to stay in the shipping container forever… my business model was to pilot it for two or three years… and if it did pencil to scale, then to move into a 10 000 square foot warehouse.' • 'I decided to get a shipping container because it was a one-man scale [operation] that I could manage.' • 'Certainly, from a research standpoint and the student learning perspective, I think there's a lot of opportunity.'

The second most common HCF goal ($n = 8$) was to create positive social impact. Organizations using their farms in this way aimed to create community engagement, workforce development, or education about farming and healthy eating: 'the [HCF] is just one of those ways in which we're able to… harness… technology and innovation to create change [in our community],' one subject noted. Some of these programs focused on helping specific groups, such as veterans or individuals with disabilities, or causes, such as using the HCF as a platform for mental health counseling or job training. Among these organizations, some sold their produce or used it on-site, while others donated it to community groups or food banks. All five community-based organizations used their HCF for social impact, as well as three for-profit businesses whose primary income came from other services they offered rather than from HCF crops.

Five organizations used the HCF predominantly as an educational tool. K-12 schools incorporated the HCF into math, science, and business curricula, or even developed new courses centered on the HCF itself. Respondents shared that the HCF provided a platform for students to develop skills in farming, handiness, workforce readiness, teamwork, and personal responsibility. At colleges and universities, the HCFs were intended to facilitate student research, provide education on healthy eating, bring in classes for tours, and build upon university sustainability and innovation initiatives. All three of the K-12 schools interviewed and two of the colleges and universities used their HCFs primarily for education.

Finally, two organizations used the HCFs primarily for research. This includes one university operating an HCF in partnership among groups within and outside the school, and one for-profit business using the HCF as a pilot system to investigate expansion into larger-scale CEA. Both appreciated that the HCF was the 'easiest to get into place,' as one farmer put it, due to its flexible site requirements compared to alternatives like retrofitting a warehouse. While research was the primary function of the HCF in these organizations now, both farmers described longer-term goals of positive community impacts and creating CEA jobs, suggesting that the primary goal that organizations envision for HCFs may evolve over time.

3.1.3. HCF operation within differing organizational structures

Across all four types of organizations described above, there were two models of organizational structure in which HCFs operated. At 15 of the organizations, the HCF was operating under a larger parent organization that existed prior to their acquisition of the farm, including universities, restaurants, food banks, and nonprofit organizations. At the other 11 organizations, the HCF itself formed the core of the business. These independent organizations started up simultaneously with the acquisition of the HCF and, from the beginning, used a business model developed around the farm's operation. The nature of the organizational structures (see figure 3) had a strong influence on motivations, perspectives, and challenges of HCF use, as described below.

Most of the 15 parent organizations operating HCFs were not food-centered entities. In these cases, the HCFs were obtained to advance the organization's overall mission through the benefits the farm could provide. For example, educational and community organizations saw the HCF as a tool to contribute to skill-building, community engagement, or to 'provide educational opportunities around water conservation, newer agro-tech opportunities, and also business agriculture,' one subject described. At only three of these 15 organizations was the HCF operating predominantly as a food production tool. These findings underscore the challenge of assessing HCF success through traditional economic or agricultural metrics, as their value may not hinge only on food production capabilities, but on other ancillary benefits they provide.

Among the 11 independent HCF organizations, one was a community-based organization and the other ten were for-profit businesses focused on growing and selling HCF produce. In contrast to those under parent organizations, motivations for HCF adoption among independent organizations were often driven by personal goals, experiences, and perspectives of the founders and farmers themselves. For example, individuals at seven organizations obtained their HCF because they were personally interested in vertical farming or sustainability ('I had a totally different career, and then I decided I wanted to switch into something that I love'), or had experimented with CEA as a hobby and decided to expand into a business. Five subjects were motivated by a perceived business opportunity in agriculture: one such farmer said, 'I was really looking for an industry that… was ripe for innovation.' Three farmers saw the HCF as a solution to local challenges they witnessed, including a lack of fresh, local produce or the vulnerability of local food supply due to the geographic isolation of their communities.

3.2. Common challenges and opportunities span HCF adoption and operation

While the above results illustrate how goals for and perceived benefits of HCF use varied across organizations, interview findings also identified several areas of commonality. Specifically, individuals and organizations go through four common stages of deciding to obtain and determining how to fund their HCF, finding an appropriate location, learning operational practices, and maintaining production over time. Each of these themes is discussed below.

3.2.1. Deciding how to obtain and fund the HCF

Subjects sought information from many sources when deciding to obtain an HCF. Four subjects visited operational HCFs before purchasing their own farms, and lessons learned from any previous agriculture experience were often influential. Those operating the HCF as an independent for-profit business emphasized the importance of developing a robust business plan prior to obtaining the farm. Many spent time investigating the conditions of their local market: they sought out and spoke to potential customers to gauge interest and assess expected price points, which for some, 'took a lot of time, a lot of planning… to really solidify the market that we needed, as well as knowing how much… [we can] sell a product for.'

Determining how to fund the capital cost of the farm was an early consideration. The two most common funding sources discussed were loans that partially or fully covered the capital cost ($n = 4$) and contributions from farmers' personal savings ($n = 4$). Four organizations received their HCFs as donations with no capital expense, most commonly from local philanthropic organizations. Two organizations secured grants to fund a portion of the capital cost, though it was more common for organizations to use grants to fund operating costs or special projects using the HCF ($n = 5$).

The high cost of buying an HCF from a manufacturer was an early barrier for many organizations, given that turnkey systems sell for up to $169 000 (Freight Farms, n.d.-b), in addition to costs of farm delivery and site preparation. Purchasing from a manufacturer was justified by some farmers as paying for both the farm and its 'tuition,' in the form of the education and support most manufacturers offer as farmers learn to use the HCF. One farmer also explained that purchasing a proven system made it easier to secure a loan compared to building their own custom farm. However, the high price was challenging for some organizations. A few subjects described how paying back the capital cost loan over the first few years of HCF operation limited profitability during this time, and several felt that building out a custom system with a lower upfront cost would be the only way to make HCFs profitable at scale.

3.2.2. Siting the HCF

Finding an appropriate site to place the HCF was among the most critical first steps respondents described in beginning operation. Despite the potential for HCFs to operate in nearly any location, subjects preferred sites in close proximity to both the food's point of consumption and the farmer's home or other place of work. The farms require access to electricity and water, which can limit feasible locations. For those operating in urban areas, high rent costs also rendered some locations unaffordable: 'if you're renting space, that's another huge overhead,' one said. Alternatively, those with the opportunity to place the HCF on land they or their organization already owned saw significant cost savings.

The issues of local zoning and permitting regulations arose frequently in interviews, but their impact varied widely by location. Five subjects described positive local ordinances that generally favored agriculture and were supportive of the HCF because, 'agriculture is king,' as one farmer described their area. Independent farmers operating HCFs in these areas were often able to place the HCF on residentially-zoned land they already owned, though this occasionally came with mild initial pushback from neighbors. Farmers who encountered support and excitement from local decision makers experienced an overall easier time obtaining permits or exemptions needed to site their HCFs.

However, seven subjects faced notable challenges under unsupportive local zoning regulations that made it difficult to find a permissible location for the HCF. Six of these seven farmers described the root of their challenges as a mismatch between zoning laws and the unique technology of HCFs, with one stating: 'all of the agriculture zoning laws in this area were done… back when farming was a completely different thing.' This farmer spent over a year working with county officials to obtain permits and approvals needed to site their farm. Another farmer explained that 'the technology and what we're doing is ahead of regulatory bodies. They don't really know what to have as a permit.' Some farmers had to work around these limitations by obtaining permits for the HCFs within other existing categories, including 'climate-controlled storage,' a 'tool crib,' or even a small 'laboratory.'

3.2.3. Learning to operate the HCF

All farmers went through a period of learning to operate their farms. Seven subjects described the learning curve as 'big' or 'steep,' with one noting that learning to operate the HCF was 'a lot harder than you think.' The role of previous agriculture experience in mitigating the learning curve varied: previous work with CEA systems was generally helpful, but four subjects who had worked only with traditional agriculture in the past said their experiences were not directly transferable to HCF farming. Four other subjects who did not have any previous agriculture experience felt that their lack of knowledge contributed to a steeper learning curve.

Regardless of previous experience, subjects used a variety of information sources to learn how to operate their farms. While trial and error was most common, at least 12 subjects used educational material provided by the HCF company from which they purchased their farm. Such material included online articles and videos, in-person training, support by phone, and live roundtable discussions hosted by manufacturers. For some, the value of these resources contributed to the benefits of the HCF itself over other farming methods. As one described: 'to me, [HCFs are] really amazing because they can lower the barrier of entry [to] agriculture for people… myself included, where I didn't necessarily have a background in agriculture, even gardening. And I've gone to [the manufacturer] and had all the tools I needed to learn how to use [the HCF].' Many subjects also learned from and shared ideas with other farmers, though this was seen almost exclusively between those using Freight Farms systems rather than other brands.

3.2.4. Maintaining HCF operation

Choosing which crops to grow was an ongoing consideration for farmers. Among the biggest drivers of crop choice (figure 2) were characteristics of the local market, such as the level of market saturation among potential produce. Some chose to grow popular crops, like romaine lettuce, which would appeal to a broad customer base, whereas others developed relationships with customers and grew specialty items to establish a niche that only they could supply locally—choosing less-common crops like deer tongue lettuce or kohlrabi. Logistic factors also played a role in crop choice: for example, farmers often preferred crops with a fast growth rate between seeding and harvesting. A few subjects prioritized growing what would most benefit their local communities, such as crops that were culturally important to local consumers ('There's a large Portuguese population, so we [make] a kale soup… and so we grow all our own kale'), or staple food crops to best address local hunger needs. For example, one business who donates HCF crops to food pantries stopped growing basil during the COVID-19 pandemic and instead grew exclusively lettuce to better address recipient needs.

Among those selling their produce, the most common outlets were direct-to-consumer markets ($n = 13$), including community supported agriculture (CSA), online ordering for pickup or delivery, and on-site farm stands. Some sold to restaurants ($n = 9$), as well as grocery stores ($n = 5$), retailers ($n = 4$), and produce distributors ($n = 2$). Overall, farmers favored markets with a high profit margin, consistent demand, fewer food safety regulations, and lower labor requirements. One farmer contrasted selling bulk orders to a restaurant to individual orders through a CSA: 'I have one restaurant that buys a thousand plus heads [of lettuce] a week from me. And so [I went] from… that, where it's one customer, one delivery, one invoice, to 70 customers, 70 deliveries, 70 packages, 70 invoices. So it just drastically changed the amount of labor that went into actually making a CSA work.'

Strategies to find customers varied by market type: farmers using direct-to-consumer models typically used social media and word of mouth, whereas most restaurant customers were acquired by bringing produce samples to chefs in-person. Some subjects found that the farm itself was a good marketing tool, as it could be 'a draw to get people into the door, at least initially,' as one described. However, others found this strategy less effective, noting 'I didn't try to oversell the container because you're not selling technology to chefs, you're selling the greens.' These farmers chose instead to emphasize the added value of HCF-grown produce compared to conventional produce (e.g. the HCF's resistance to adverse weather makes its supply more consistent and predictable). When setting prices, farmers' rates depended on both the income needed to cover operational costs and their perceived product niche within the market. Most saw their crops as a superior product in terms of flavor and quality compared to conventional alternatives, and thus asked higher prices.

Managing the labor required to operate the HCF was a frequent challenge among organizations. For example, K-12 schools commonly struggled to staff the HCF outside the academic year. When those tasked with managing the HCF had other full-time duties within the organization (e.g. as a teacher or a chef), the HCF often became a lower priority, and parent organizations generally benefited from hiring an employee specifically to manage the farm. For independent for-profit organizations, the cost of labor compared to HCF income made it difficult to afford desired levels of staffing. A compounding challenge was the inability to automate processes within the HCF to reduce labor requirements: 'until you are seeding, cleaning gutters, basically automating the entire harvest and packaging system, labor is going to haunt you,' one farmer explained. Some subjects viewed the combination of high labor cost and low automation potential to be a significant limiting factor to HCF scalability.

3.3. HCF use results in a variety of outcomes within the food system

A key motivation for this research was to better understand how HCFs are being used in the food system, and, in turn, begin to characterize social, economic, and environmental benefits or tradeoffs their use may create. Results described in this section show that the evaluation of such outcomes by farmers is ultimately tied to their individual experience using the HCF. Despite the commonalities in how farmers obtain, set up, and use the HCF, there was no single way in which they assessed the farms' performance or its broader role in the food system.

3.3.1. Metrics of HCF success

How farmers quantify success of their HCF largely depended on their goal for the farm. Farmers operating with a food production goal often put greater emphasis on agricultural performance parameters like yield and crop quality. Some organizations focusing on social impact measured their success quantifiably; for example, one community organization said: 'we judge [impact on the overall community] by… how many kids go in there, how many actual people get trained to understand the workings of the farm.' But another similar organization was shifting away from numeric results, noting the need to be, 'really careful about not saying that the impact [of the HCF] needs to be quantitatively higher or bigger or wider.' One farmer at a university highlighted how their goal of educating future farmers outweighed agricultural successes, and that despite facing numerous technical challenges that reduced yields, still rated their experience with the HCF very positively. They explained: 'We did come across some problems… but ultimately… It's an educational farm. If I lose a hundred plants, I'm not going to freak out about it, I'm going to learn from that… moving forward, sharing this information with the future farmers.'

Regardless of the goal of the HCF, many farmers considered customer feedback an important metric of success. Across interviews, subjects described these reactions as overwhelmingly positive. The most frequently mentioned comments from consumers related to produce freshness, long shelf life, and good flavor. Consumers also appreciated knowing where their food was coming from and liked the small-scale and local feel of buying from the HCF. Negative feedback was less common, though one subject described how the lack of environmental stressors inside the container produced greens with soft leaves, which customers said were not, 'hardy enough to hold up… other vegetables on top of the lettuce' in salads. These results are consistent with past work showing the importance of consumer perceptions of sensory qualities when evaluating hydroponic crops (Treftz and Omaye 2016) as well as the difficulty in universally comparing the quality of hydroponic and conventionally grown crops (Murphy *et al* 2011, Treftz and Omaye 2015, Lei and Engeseth 2021).

Among those using the HCF for education, subjects described a range of positive outcomes. At colleges and universities, farmers often hired students to work in the farm or participate in HCF research, while at K-12 schools the HCF was used to augment classroom instruction. For example, one high school built a business class around the HCF where they operated the farm as an example business. Another school took inspiration from the HCF to add curriculum on issues of food insecurity and organic and fair-trade labeling, noting: 'I don't think the farm itself drives the environmental justice curriculum, though the fact that it existed made it so we started putting that in our curriculum.' Subjects also mentioned largely positive feedback school administrators, educators, and parents.

Intentions to expand growing capacity were also directly influenced by farmers' experiences. Among the 18 subjects who discussed their organizations' future plans, ten intend on adding growing capacity. While some plan to do this by obtaining additional HCFs, others were considering alternative growing methods (most commonly greenhouses and warehouse farms). This was primarily due to a perceived lack of scalability in HCFs because of their high labor requirements, and less related to other potential downsides like the relatively limited crop choice available in the HCF compared to a greenhouse or warehouse. For HCFs operating under a parent organization, future growth in farm capacity is sometimes driven by demand for the prime business; as one farmer stated: 'I'm allowing my therapy business to dictate the expansion of the farm operation, so once we… outgrow… our current space, then we'll look to obtain another farm.'

3.3.2. Roles of the container farm design and structure

A key theme that arose from interviews was that evaluation of success was largely influenced by how farmers perceived the strengths and weaknesses of the physical infrastructure comprising the HCF. Figure 4 shows exterior and interior images of a typical HCF model, along with benefits and drawbacks of the design that were commonly noted in interviews. The most frequently mentioned strength of the shipping container model ($n = 10$) was its complete physical barrier from the outside environment. Five subjects also appreciated being able to operate modular, replicated farm units. One farmer who works with adults with disabilities described how modularity can increase accessibility by enabling distribution of farms throughout residential areas, which would be easier to access than a single central location. However, they also noted that the shipping container itself is not accessible to those using wheelchairs. Five subjects described how the shipping container structure would enable their ability to build out by adding more containers and quickly scale up production due to the 'plug-and-play' design, compared to alternatives that have a longer construction period.

However, other farmers noted drawbacks of the shipping container structure. The most commonly described issues ($n = 8$) were related to the small interior space, which was most concerning for schools and other organizations that hoped to bring many individuals into the HCF, since, 'you're not going to be able to get more than three or four people in these shipping containers at a time,' as one stated. Space limitations meant that organizations often had to compromise on competing goals. For example, a densely-planted HCF used primarily for food production will not have space needed for many students to come inside to learn, while an education-focused farm with more space for students will not maximize yields and may be more susceptible to the introduction of pests or disease. The high energy demand—primarily due to the lighting and HVAC systems—is also noted as a drawback from cost and environmental perspectives.

Subjects' ultimate impressions of success were also influenced by the design of growing systems inside the HCF. The majority of subjects ($n = 23$) were using HCFs with vertical-plane hydroponic channels, 18 of which were operating the same HCF design from one manufacturer. Subjects generally liked this model's simplicity and that the standardized design enabled farmers to easily share knowledge with others using identical systems. However, the vertical LED lighting was commonly criticized for being too dim. Updated

Shipping container exterior structure

Benefits
- Fully-controllable, year-round growing environment
- Operable in a wide variety of siting conditions
- Modular, replicable units enable individual growing environments
- Protects against pest outbreaks between containers
- Pleasant work environment
- "Coolness" draws attention
- Small footprint

Drawbacks
- Eliminates free energy available from sunlight
- Few people can fit inside at once
- Dense planting enables pests and disease to spread quickly
- Lack of environmental stressors can cause weak and limp produce
- Highly-controlled environment means small user errors can devastate crops

HCF interior design

Benefits
- Hands-on educational opportunities: e.g., in agriculture, technology, teamwork, business
- Efficient water use
- New models improved upon over older models in lighting, labor requirements, and overall design
- Models that enable in-place harvesting require less labor
- Stacked NFT reduces labor vs. vertical channels

Drawbacks
- High energy use
- High heat load from lighting increases AC use
- Some crops are not well-suited to growing in the vertical plane
- Lighting system in some models is too dim
- Difficult to reach plants in the back of stacked NFT channels
- Some vertical plane systems can be susceptible to water leaks

Figure 4. Sample photos of an HCF. On the left is the shipping container exterior structure; on the right is the container interior design showing an example of vertical-plane hydroponic channels. Also included are comments that arose in interviews that reflect subjects' opinions on the benefits and drawbacks of each aspect of HCF design. Subjects' perceptions of the HCF's overall success hinge on their perceptions of both the shipping container structure and the design of the growing system inside, which they frequently discussed in interviews. In this figure, NFT stands for 'nutrient film technique'—a method of growing crops in horizontal-plane hydroponic channels. Photos used with permission from RIT/Gabrielle Plucknette-DeVito.

HCF models with a modified vertical-plane design were viewed more favorably, with respondents noting the improved vertical lighting system and movable racks that allow in-place harvesting. However, several subjects also noted concern about crop vulnerability as the design offers little room for error, with one elaborating: 'you're fully controlling [the environment], so any mistake you make is going to be amplified.'

To better suit the needs of their organizations, some subjects customized their HCF over time. Some added additional growing sites to increase yield or to enable the ability to grow crops not supported by the HCF infrastructure initially, like cucumbers or microgreens. Others removed growing area to create open space for social interactions inside the farm. Some customizations aimed to improve performance (e.g. installing additional infrastructure like water tanks, fans, and dehumidifiers), while troubleshooting solutions were sometimes sought to address unanticipated issues, such as covering the outdoor lock to prevent freezing and covering exposed pipes and gutters to shade them from light that promoted algae growth. While some farmers were frustrated with the need to adjust their plug-and-play systems, others took it as part of the learning process and were proud of their solutions. Compared to the larger components of the overall HCF, these smaller design issues did not significantly influence farmers' perceptions of HCF success.

3.3.3. Perceived future potential of HCFs

When asked to consider future potential of HCF systems, many respondents reflected on the major lessons learned during their HCF farming experience. Common suggestions were that new farmers should consider all potential growing systems before choosing an HCF, define a clear goal for the farm from the start, and acknowledge tradeoffs early on. Several emphasized the importance of being realistic about projected yields and being cautious of optimistic marketing from HCF manufacturers regarding performance. A few subjects also mentioned the need to be prepared for numerous and time-consuming tasks beyond farming that also come with operating an HCF, especially as a business. One said, 'I think some people forget about all the backend stuff like the billing, the marketing, the website… the accounting aspect, taxes, all that type of stuff. So, there's a lot more than just plugging it in and letting it go.'

Regarding its niche among other agricultural methods, interviews suggested that the HCF may act as a bridge between different forms or scales of production. For some, the HCF built on existing agricultural activities conducted personally or within the parent organization. In these cases, the HCF provided new benefits like greater use of technology or a lengthened growing season. For others, the HCF was used as a first step towards larger CEA, such as a warehouse farm. Several respondents were using the HCF as a pilot to

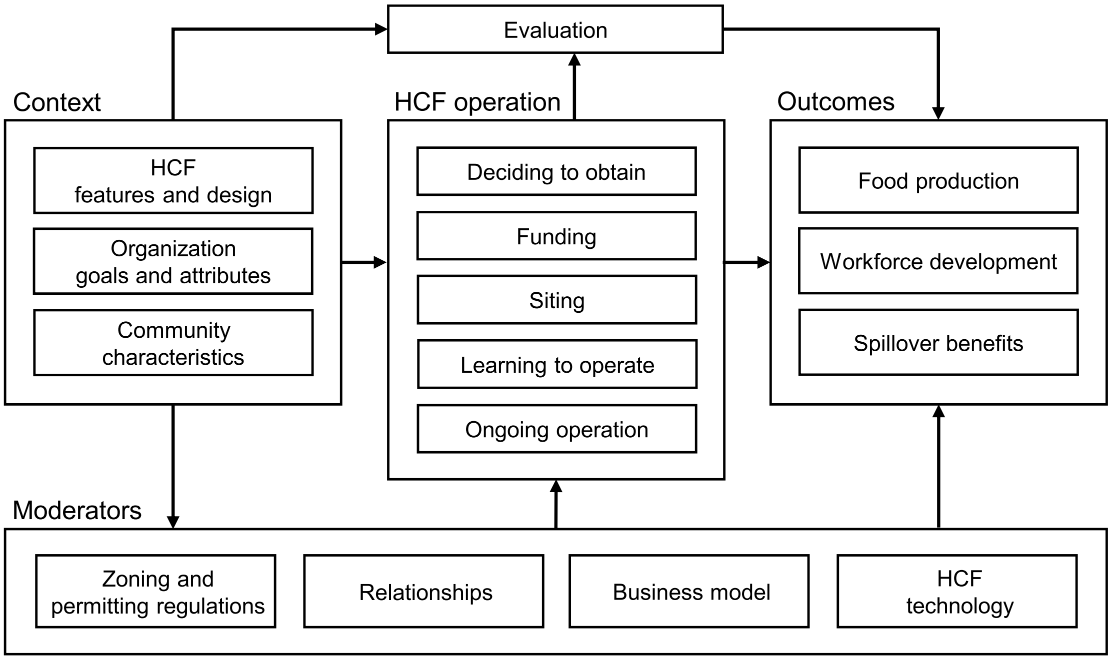

Figure 5. Conceptual diagram that shows the process of HCF operation and evaluation of potential impact within the broader food system.

prepare for scaling up in the future: '[the HCF] was something that I thought would be a stepping stone, I'd learn it and then move on,' one farmer explained.

There were conflicting opinions on the HCF's potential to operate as a profitable business. Seven subjects expressed that HCFs are most successful when profit generation is not a requirement of operation, as when used primarily for education, social engagement, or hobby farming. The most frequently mentioned factor that limits the HCF's use as a business is a lack of scalability, which is primarily driven by labor requirements and associated costs. The issue of scalability is exacerbated by space constraints inside the container, which some noted would confound the ability to introduce automation into the farms to reduce labor needs. This sentiment was not ubiquitous among all subjects though, as two organizations interviewed were operating four or more HCFs—both with intentions of obtaining more in the future—and another farmer described long-term plans to operate over 100 HCFs.

Subjects' experiences informed their opinions on the role HCFs can play more broadly in the food system. Seven subjects consider the HCF's biggest advantage to be enabling farming in otherwise uncultivable areas, including urban areas and locations with climates unsupportive of traditional agriculture. Three farmers acknowledged that the HCF has positive uses but will not be the best option for every situation: '[the HCF is] never going to be the only solution, we have to feed our soil and take care of the land… that's also really important,' one emphasized. When the goal is to operate for profit, at least three farmers emphasized the approach of growing specialty crops and selling to high-end restaurants that can afford to pass the cost on to customers. Despite challenges, many farmers agreed that the HCF was a step in the right direction within an industry in need of innovation: 'I think that eventually it'll become more important to just have [HCFs] in your community to benefit… others.'

4. Implications

Farmers' perspectives on their experiences operating HCFs can inform a broader picture of the role of HCFs might play in the food system and guide future work quantifying their sustainability impacts. Interviews show that HCFs are currently producing both direct and indirect benefits. The extent to which these benefits are realized in practice is moderated by the broader context of HCF operation, in terms of local zoning, produce market characteristics, and personal relationships between farmers and collaborators, all of which can either be enablers or barriers. Figure 5 shows the relationships between the context and operation of the HCF, the outcome of operations, the factors that moderate HCF use, and overall evaluation of HCF success. These relationships are discussed further in the following sections.

4.1. HCFs contribute both direct and indirect benefits to the food system

HCFs are being used successfully in the food system to grow crops, with many farmers achieving consistent harvests. The fully controlled environment and ability to schedule crops long in advance with high confidence helps farmers compete against other suppliers and develop close, collaborative relationships with customers. The ability to grow high quality and diverse crops in HCFs enables farmers to fill niches in their market, particularly where customers are interested in the local, personal feel of buying from farmers within their communities.

HCFs are also contributing more broadly to the food system by supporting some workforce development in agriculture. HCFs' minimal site requirements, turnkey nature, and quick startup time help provide access to farming to those who do not have arable land, open space, or knowledge required for conventional growing systems. HCF manufacturers play a role in providing support and resources for new farmers, potentially overcoming the identified barrier of lack of technical knowledge about CEA operation (Wagner *et al* 2021, Pomoni *et al* 2023). HCFs are also used to educate students and raise awareness of careers in agriculture, which is particularly valuable due to the aging population of U.S. farm workers (USDA NASS 2019). Additionally, HCFs provide meaningful employment and job training opportunities for individuals with disabilities. While other CEA businesses hire individuals with disabilities to work at centralized CEA farms (e.g. Vertical Harvest (Vertical Harvest 2023), Greens Do Good (Greens Do Good 2023), Lettuce Dream (Lettuce Dream 2023)), the decentralized and modular form of the HCF can enable access for individuals with limited mobility.

HCFs also generate spillover benefits during operation. Farmers enjoy what they describe as fulfilling tasks and a pleasant or even meditative working environment. Organizations leverage this environment to foster teamwork among students or therapeutic and mental health support for clients. The produce grown in HCFs was seen to encourage healthy eating among K-12 students, a population for which food literacy is key to shaping healthier diets (Vaitkeviciute *et al* 2014). The potential educational benefits of HCFs also went beyond farming, and included business, math, marketing, advertising, and environmental sustainability. Educational potential extended into the larger community when farmers offered tours, open houses, volunteering, and internship opportunities.

4.2. There are universal moderators that impact HCF feasibility and outcomes

Across interviews, key factors were found to strongly influence HCF success. One such factor was the ability to navigate local zoning regulations to obtain an appropriate site for the HCF. Farmers in locations with restrictive regulations went through a notably more difficult and lengthy siting process compared to those in areas with fewer restrictions. These barriers were commonly linked to a mismatch between municipal policies aimed at large, centralized agricultural or industrial operations and the small size and scale at which HCFs operate. These are challenges shared by other small-scale urban food operations, including urban gardens (Patel and MacRae 2012), composting facilities (Ai and Zheng 2019), and small-scale biowaste management (Angouria–Tsorochidou *et al* 2021). Support from local decision-makers was invaluable for obtaining HCF permits and variances, whereas negative misconceptions or lack of knowledge about the technology was detrimental and delayed farm siting. For example, when seeking to place an HCF on residential property, some farmers experienced pushback from neighbors—an issue previously identified as a challenge to urban CSAs (Patel and MacRae 2012). Some regions have now begun to update regulatory processes to support urban food systems, including New York City (Goodman and Minner 2019) and Illinois (Ai and Zheng 2019).

Another common factor in HCF success is the role of positive relationships. HCF farmers often cooperated with other local farmers to seek advice, co-host farm stands, or refer customers—creating an agricultural community (Patel and MacRae 2012) and a social structure that helps advance sustainability and circular economy (Hull *et al* 2021). Farmers also collaborated with groups like schools, businesses, and hospitals, which led to joint benefits. For example, partners provided assistance in the forms of rent-free sites, payment of electricity and water costs, or advertising through their marketing channels. In exchange, the relationship with the HCF provided them with positive publicity and advertising, agricultural tax exemptions, and engagement tools for clients or customers. The HCF farmer's willingness and ability to foster such cooperative relationships strongly influenced realized success.

Results echo past studies that have also documented the challenges in operating HCFs as a profitable business (Wagner *et al* 2021). They mirror barriers that have previously been identified in the diffusion of more broad climate-smart agricultural technologies—including difficulty accessing startup capital, working in an unsupportive policy landscape, and managing overly long return on investment periods (Long *et al* 2016b). However, those who did find success with their HCFs noted the importance of developing a business model that balances the farm's high capital cost and ongoing operating costs like electricity and labor with a plan to achieve profitability in their local market. Subjects best able to balance these costs were those who did significant research into the local market before obtaining their HCF and ensured that their realistic revenue stream would be enough to offset anticipated costs. Successful businesses also added resilience to their business model by creating additional revenue streams outside of farming, including creating educational videos and resources and hosting fee-based tours.

Finally, because HCF use and goals were found to vary so widely, farmers would likely benefit from greater diversity in HCF designs and price-points, particularly to address the high capital investment required for hydroponic systems (Pomoni *et al* 2023). The 'plug-and-play' product and extensive training that many manufacturers offer are valuable tools, but are not equally valued by organizations due to the heterogeneity in HCF use in terms of farmers' experience levels, organizational goals for the farm, and desired crop choice. Some are willing to pay a high capital cost in return for the advanced technology and customer support from the manufacturer, but others may be unwilling or unable to pay more for features they may not need or a farm design that is misaligned with their goals (e.g. a community-focused farm may not need the newest technology; an experienced farmer may not require extensive support).

4.3. Limitations and future research needs

As a qualitative study based on grounded theory methodology, findings are not meant to be fully generalizable to every individual's experience. The sample size of 26 organizations interviewed represents a broad cross-section of HCFs currently in use in the U.S., but each individual and organization holds a unique experience. However, many themes were represented so strongly across interviews that they are likely to be shared by other U.S.-based HCF farmers, and possibly even by other users of small-scale technologies in the food system. These results point to key opportunities for future research to advance understanding of the opportunities and barriers faced by these food system actors.

Since the geographic scope of this research assessed U.S.-based organizations, it is unclear if the results are applicable to organizations operating in other regions. However, literature on CEA systems operating elsewhere in the world reveals similar findings. For example, a review of varying types of hydroponic systems in use globally corroborated benefits related to efficient water use and usability in urban centers, as well as challenges related to a high initial capital investment, high energy use, and the need for specialized technical knowledge (Pomoni *et al* 2023). An analysis of urban farms across four continents revealed zoning, permitting, and building regulations as obstacles to farming in cities (Thomaier *et al* 2015), and studies in both Japan (Kubo and Okoso 2019) and Indonesia (Harniati *et al* 2023) investigated how successful business models can be created to support new forms of hydroponic growing. More research is needed to fully explore the impact of geographic variability on benefits and drawbacks of HCF use, including the influence of local climate, policies, and markets on HCF adoption and barriers.

Findings from this study also have implications for further research on sustainability assessment. Many subjects alluded to potential environmental benefits or tradeoffs of HCF use, but did not explicitly discuss these outcomes or their quantification. Methods such as life cycle assessment are needed to quantify environmental impact of HCFs relative to the varied use cases documented in this study and investigate environmental tradeoffs of growing specific crops via HCF compared to conventional farming or other CEA methods. Future research should also continue to investigate the financial viability and opportunity of HCFs as a business by quantifying costs and revenue opportunities in different markets.

However, such economic and environmental comparisons require that alternatives be evaluated on the basis of comparable functionality, such as the number of units produced or total crop yield. Results presented here show the difficulty of establishing an equivalent comparative basis when evaluating HCFs, as these systems are often being used to provide functionalities beyond food production or economic profit. In some cases, HCFs might be more reasonably compared to other types of social interventions or educational tools, rather than to existing farming systems. Thus, one clear research need is better documentation of HCF performance using metrics that can capture social, economic, and environmental dimensions of organizational benefits or leverage more standardized measurements of educational (Patchen *et al* 2017) or health (Kwok *et al* 2021) outcomes.

5. Conclusion

With increasing need for and interest in agricultural innovations, HCF adoption and use has expanded across a wide array of settings and organizations. This work explored the role, challenges, and opportunities for HCFs in the food system from the perspective of farmers responsible for their operation. Findings show that on one hand, there is a high degree of commonality in the experiences and challenges that organizations go through while deciding to obtain an HCF, starting up their system, and maintaining operation over time. On the other hand, there is significant variability in the goals organizations have for the HCFs, views on if and how the HCF was successful in meeting those goals, and on the broader roles these systems may play in the urban food system. HCF adoption was linked to direct food system benefits, including local food production and agricultural workforce development, as well as positive spillover benefits for students, workers, and communities. The role of HCF manufacturers in supplying 'turnkey' farming systems and ongoing support to farmers helped enable these benefits and increase access to agriculture for those without previous experience. However, the relatively narrow range of design options, high capital cost, and low automation potential may limit wide adoption of HCFs. Some factors that may enable broader use and benefits are improved zoning and permitting ordinances, cooperative community relationships, and a well-prepared business model appropriate for the HCF and the market in which it operates. Given the challenges facing conventional agriculture, it will be important to continue to investigate the potential role of HCFs and other CEA growing methods in the food system.

Data availability statement

The data cannot be made publicly available upon publication because they contain sensitive personal information. The data that support the findings of this study are available upon reasonable request from the authors.

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Ethics statement

This human subjects research study was conducted in accordance with all statutory requirements and was approved by the Rochester Institute of Technology Human Subjects Research Office (HSRO) and Institutional Review Board (IRB)—Approval: 01100220. All adult participants provided written and/or recorded informed consent to participate in this study. Any identifiable individuals or organizations shown in the article are not participants in the study and have provided consent for their image to be used.

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