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Opportunities and challenges of vertical farming to contribute to the sustainability of food systems in Canada

A *Research* Report prepared for CAPI by
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Research
Report

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To ensure the validity and quality of its work, CAPI requires all *Research* Reports to go through a peer review process. CAPI thanks the Doctoral Fellows Mentors who provided expertise, guidance, and feedback on these reports throughout the first year of this fellowship: Aaron Cosbey, Cam Dahl, Dr. Karen Hand, and Dr. Lenore Newman. The views and opinions expressed in this paper are solely those of the authors and do not necessarily reflect those of CAPI.

Note from CAPI

CAPI recognizes the importance of fostering and mentoring the next generation of thought leaders emerging from Doctoral programs across Canada, who are working in multi-disciplinary fields. Through this program, CAPI offers a small, innovative group of young students the opportunity to apply their newfound knowledge and expertise to some of agriculture's most critical policy issues.

The third cohort of CAPI Doctoral Fellows (2022-2024) was tasked with focusing their research on the intersection of agricultural trade, the environment and food security and this paper is one of the results. In light of recent trade disruptions, food security concerns and climate change commitments, CAPI is interested in how they are impacting Canadian agriculture and agri-food and the policy implications. This paper is the first deliverable in the first year of the two year program, showcasing the interdisciplinary nature of the fellows' research as it relates to the opportunities and challenges of vertical farming and sustainable food systems in Canada.

This Fellowship is supported in part by the RBC Foundation through RBC Tech for Nature as part of CAPI's larger environmental initiative, Spearheading Sustainable Solutions.

Key Takeaways

- The potential opportunities and challenges of vertical farming to contribute to the sustainability of food systems in Canada are relative to multiple factors across the fields of engineering, management, and crop science. This includes the types of crops to produce, technical characteristics, location, and intended markets.
- The multidimensional nature involved in the sustainability of a food system entails potential trade-offs among sustainability goals. Therefore, a necessary step to provide insights into the direction that further research on vertical farming should take in Canada is to define the purpose for their implementation in each context and/or region, prioritizing the sustainability outcomes expected from their implementation.
- Envisioning vertical farming with a lens of multifunctionality may be key for their feasibility. This may include combining various crops, offering additional services, and implementing synergies with local and surrounding businesses within the concept of circular economy.
- Producing crops in highly controlled environments requires continuous availability of inputs such as seeds, fertilizers, water, and electricity. Provided that sustainability builds on enhanced resilience and reduced vulnerability, the availability of these resources must be ensured. Further, if the vision is to increase local and/or domestic crop production in Canada, increased resource uptake and domestic GHGs should be acknowledged as potential trade-offs.

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Abstract

There is widespread awareness of the vulnerability of our food systems facing multiple disruptions, and of the need for implementing innovative agricultural solutions to introduce transformative changes towards more resilient and sustainable food systems. Vertical farming is a type of farming in controlled environments, providing the possibility of producing locally, while obtaining consistent and continuous crops in controlled environments. The concept might represent opportunities in the sustainability of food systems in countries such as Canada, which depends widely on imports to supply fresh fruits and vegetables. However, these technologies are also questioned from several fronts, and existing studies providing empirical data to support the discussion on their potential contribution to more sustainable food systems remain scarce. From the review of literature on the sustainability of vertical farming in Canada, this study concluded that the potential opportunities and challenges of vertical farming to contribute to the sustainability of food systems in Canada are relative to multiple factors associated with their planning, location and design, and further research is needed based on a clear definition of their expected role in food systems in Canada.

Introduction

Canada is one of the top-performing countries in terms of food security, affordability, availability, quality, and safety (Economist Impact 2022), but its dependence on imports to supply fresh fruits and vegetables might make its food system vulnerable (Zerriffi et al. 2022). In fact, Canada imports roughly 70% of its fresh fruits and vegetables (Government of Canada, 2023), and would need to double these imports by 2030 if its population adopted healthier diets (FABLE, 2020). Further, the imports of fruits and vegetables in Canada are expected to increase to 80% in the next few decades (Zerriffi et al., 2022). As worldwide experts call for a deep transformation of our food systems to contribute to the sustainability agenda (HLPE, 2017), Canada continues to seek innovative technologies in the agri-food sector to contribute to this aim (Government of Canada, 2019). Vertical farming (VF) might play a key role in sustainably transforming food systems, providing the possibility of producing locally, while reducing barriers to accessing fresh fruits and vegetables in remote regions, and potentially reducing the need for water use, land uptake, and agrochemicals (Ramin-Shamshiri et al., 2018; Saraswat & Jain, 2021; Shao et al., 2022; Van Delden et al., 2021). However, there might also be trade-offs to the contribution of VF to the sustainability of food systems, considering their electricity requirements, and high operational costs.

While several studies address their sustainability, the performance of VF across the environmental, social, and economic dimensions of sustainability vary widely according to the characteristics of the systems assessed and depending on each context. Further, there are no existing studies addressing the opportunities and challenges of VF as solutions potentially contributing to the sustainability of food systems in Canada. This is a knowledge gap that needs to be addressed to provide insights into the direction that further research, related policies, and investments should take. This paper analyzes the opportunities and challenges of VF as a potential solution contributing to the sustainability of food systems in Canada. The first chapter provides a research outline that includes research questions and methods. A results section follows, with the review of literature on studies addressing the sustainability of VF, and on the aims and priorities of sustainable food systems in Canada. The analysis of results is presented in the discussion section, followed by the recommendations and conclusions of the study.

Research outline

Research questions

Q1. What areas of concern should be considered in assessing the sustainability of food systems and of their components?

Q2. What are the aims and priorities of sustainable food systems in Canada?

Q3. What are the opportunities and challenges of vertical farming to contribute to the sustainability of food systems in Canada?

Methodology

Q1 was addressed with a literature review of recent studies addressing the sustainability of VF. The sustainability assessment framework proposed by Hebinck et al. (2021) was selected to guide this study. This sustainability compass is based on the concept of sustainability applied to food systems and may be used for analysis at early stages of decision making, providing flexibility to reflect the reality of each context. The compass is structured across four societal goals, 16 areas of concern, and various progress indicators, to help identify potential trade-offs and synergies across the desired outcomes of sustainability, also facilitating multi-stakeholder dialogues. As suggested by the authors, the progress indicators were modified to be expressed in terms of desired outcomes for sustainable food systems, (Figure 1) providing the basis for an integrated analysis and interpretation of results.

Figure 1. Sustainability compass and desired sustainability outcomes. Note: "High animal welfare" refers to products with high animal welfare quality standards, which does not apply to this study.

Source: Adapted from Hebinck et al. (2021).

The literature review to address Q1 was conducted based on three societal goals of Hebinck's model: i) Clean and healthy planet; ii) Economically, thriving, robust food value chains; and iii) Just, ethical, and equitable food systems. The societal score of "Healthy, adequate, and safe diets for all" was found to be a consequence of the aforementioned societal scores and was considered in the analysis and interpretation of results (Q3). Q2 was addressed as a review of strategic documents towards the 2030 SDG agenda in Canada, guided by the areas of concern of Hebinck's model. Provided the scope of this study, the areas of concern of this compass were used as a guide, rather than a rubric. Q3 was addressed in the discussion section, as an integrated analysis of the results from Q1 and Q2, including an analysis of trade-offs for the desired outcomes of sustainability in food systems.

The interpretation of results is based on the theories of vulnerability and resilience in sustainability (Prosperi et al., 2016).

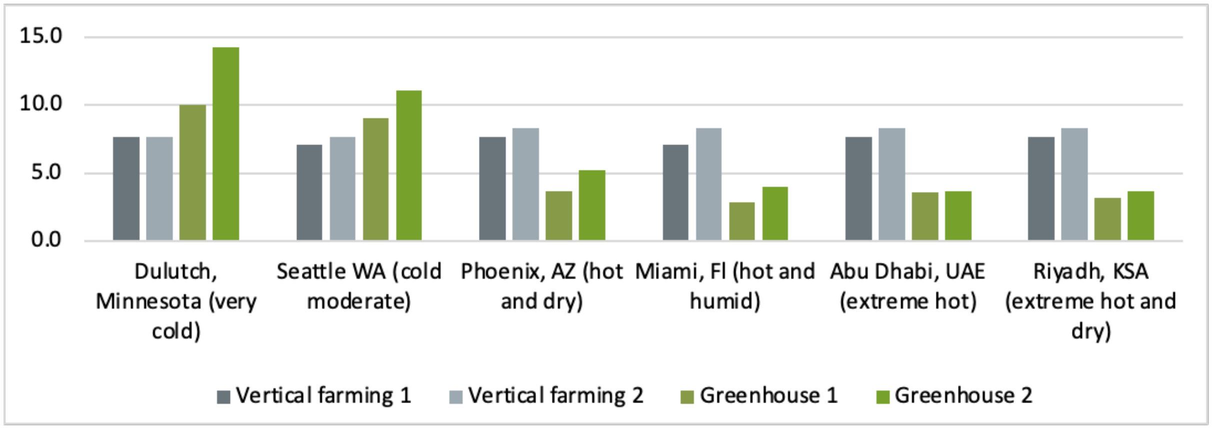
Results

Literature review on the sustainability of vertical farming (VF)

Clean and healthy planet

Energy use and GHG: VF requires the direct use of energy for technology-based processes such as artificial lighting, temperature control, and pumping. Typically, this energy is required in the form of electricity, and existing studies suggest that most of the environmental impacts and operational costs of VF stem from this requirement. Roughly, 75% – 80% is used for lighting, 12 – 25% for HVAC, and the remaining for automation, pumping, and other purposes (Kozai, 2019; Martin et al., 2022; Martin & Molin, 2019). A wide range of energy used per kg of produce in VF is found across studies, depending on the types of crops, design, scale, and technologies used. Broad ranges are encountered per crop type, including 435 – 907 kWh/kg for wheat; 62 – 130 kWh/kg for potato (Kobayashi et al., 2022); and 7 – 9 kWh/kg for lettuce (Kozai, 2019). Among each type of crop, the energy intensity of VF might be relatively consistent for different climatic conditions, in contrast to that of semi-controlled environments, such as greenhouses (Kobayashi et al., 2022). Zhang & Kacira (2020) compared two configurations of VF and greenhouses for the production of lettuce in six locations with different climates, finding relatively even values for the former (8 kWh/kg) that outperformed greenhouses in cold climates (Figure 2).

Figure 2. Energy uptake (kWh/kg) for producing lettuce in VF and greenhouses in six regions with different climates. Data: Zhang & Kacira (2020).



Source: Elaborated with data from Zhang & Kacira (2020)

Scale might also define the energy uptake of VF per unit of produce. A recent report in Controlled Environment Agriculture (CEA) based on surveys among this industry in different countries reported values of 34 kWh/kg for facilities up to 1000 m2; 15 kWh/kg for 1000 – 5000 m2; and 8 kWh/kg for facilities over 5000 m2 (WayBeyond & Agritecture LLC, 2021). However, these numbers apply to various CEA and require validation. While no studies were found addressing the influence of scale on VF energy intensity, Martin et al. (2022) suggested a consistent value of 32 kWh/kg for producing mixed leafy greens in a 100 m2 venue.

From the revision of existing studies, potential strategies to counteract and/or optimize energy use in VF may be grouped in any of three ways: i) implementing renewable energies (REs); ii) optimizing the design and control of parameters; and iii) establishing synergies with surrounding activities and businesses. Also, further development of related technologies (e.g., artificial lighting, PV systems) is often envisioned. The first approach involves the use of REs either on-grid or off-grid, typically in the form of solar PV systems, although energy from biomass/waste is also suggested (Germer et al., 2011; Martin et al., 2022). Generating off-grid electricity requires considering the feasibility of producing REs provided for climatic conditions, land availability (Kobayashi et al., 2022), and costs. Al-Chalabi (2015) analyzed the possibility of supplying the energy requirements of a hypothetical design of high-rise VF with on-site solar PV systems, concluding that self-sufficiency would be achieved for producing lettuce in buildings of up to 500 m2 in a location with high and continuous solar radiation (i.e., Phoenix, Arizona), and not including HVAC requirements. The second approach, optimizing parameters, consists of finding the best combination of multiple engineering and plant-science parameters, and requires considering potential effects on yield potential, without compromising crop quality (Asseng et al., 2020; Kozai, 2019; Van Delden et al., 2021). The dynamic and precise adjustments of operational parameters in highly controlled environments such as VF might allow maximizing productivity and optimizing resource efficiency, possibly obtaining higher yields than other forms of farming (Graamans et al., 2018; Saraswat & Jain, 2021; Van Delden et al., 2021). The third approach is to establish synergies with other activities, either in the building or in surrounding venues, to improve resource efficiency through shared flows of water, energy, and materials (Martin et al., 2022; Martin & Molin, 2019).

Global warming potential: VF allows producing crops locally, potentially reducing GHG emissions related to transport processes. However, GHGs related to food systems and to their components involve direct and indirect emissions across different stages of their life cycle. Therefore, transport processes for provisioning inputs such as seeds, growth media, and fertilizers should also be considered when estimating potential GHG reductions, which is relative to each case. The carbon footprint per kg of produce in different types of farming varies among studies depending on the scope of each analysis, which may include different stages across the lifespan of VF and related processes. For studies with similar scopes, results vary according to crop types, location, energy intensity, and technologies. Table 1 summarizes selected instances of GHGs from different farming types, although the interpretation of these numbers should consider that each estimation applies to specific designs, assumptions, and contexts. Martin et al. (2019, 2022) and Martin & Molin, (2019) studied the potential effects of different variables on the environmental performance of a hypothetical VF in Sweden, finding potential increases in GHGs if newly constructed buildings were used instead of existing venues. Further implementing on-site solar PV arrays resulted in increased GHGs, given that the electricity in Sweden is predominantly generated from REs and nuclear energy (IEA, 2022). In contrast, Li et al. (2020) found potential reductions in GHGs if electricity was provided by off-grid solar PV systems instead of the energy grid in Singapore. Back to the former studies, reductions in GHGs of up to 50% were reported for scenarios considering synergies with other activities. These scenarios had shared flows of materials, waste and/or energy. A reduction of up to 65% was reported for scenarios where packaging and growth media inputs were replaced with bio-based materials.

Table 1. Selected instances of estimated GHGs related to VF, greenhouses, and open field crops.

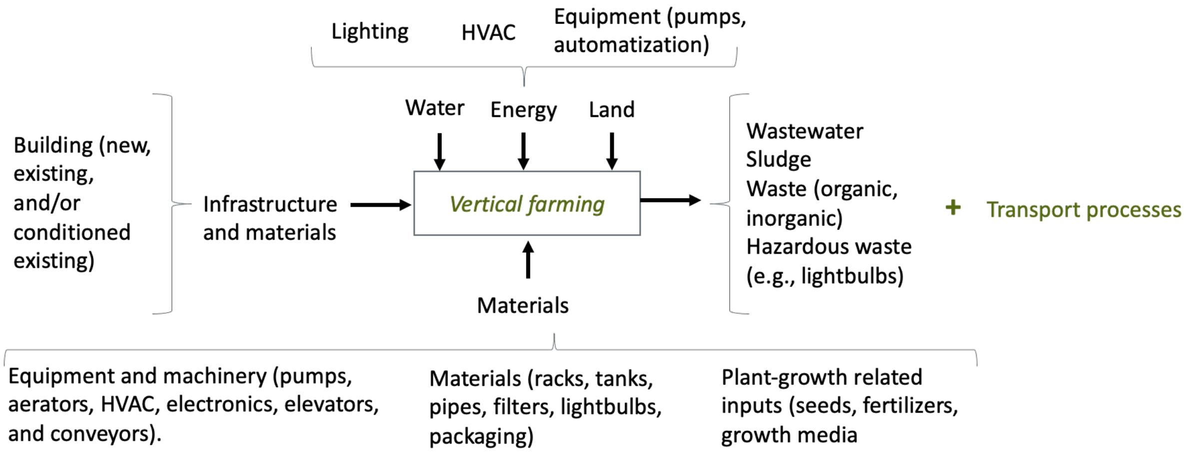
Crop (source)	Type and location	Scenario	kg CO2-e /kg	Transport
Basil (Martin and Molin, 2019)	VF, Sweden	Electricity Grid (EG)	0.74	Upstream + downstream
		EG + Improved materials	0.27 – 0.65	
Lettuce (Milestad et al., 2020)	VF, Sweden	EG	0.36	Not considered
	Greenhouse, Netherlands	EG	2.4	
	Open field, Sweden	EG	0.09	
Mixed vegetables (Li et al., 2020)	VF, Singapore	EG	1.3	Not considered
		Solar PV	0.2	
	Greenhouse, Singapore	EG	2.8	
Leafy greens (Martin et al., 2022)	Vertical farming, Sweden	EG	3.2	Upstream
		EG + symbiosis with other activities	1.5	

Land use: Land requirements in VF might vary depending on the type of crop, technology requirements, facility dimensions, and crop density. A key feature differing VF from other forms of indoor farming is the vertical component in their configuration, either on multiple levels, or columns, potentially reducing the land footprint of crops. This is also known as obtaining freed farm area. Existing studies suggest that comparisons with other types of farming should acknowledge land uptake both for crop production, and for producing electricity. Li et al. (2020) estimated the land footprint of hypothetical cases of greenhouses and VF encountering that the additional land requirements to produce the electricity required may account for 40-50% for grid-electricity, and 260-280% for off-grid solar PV systems. Kobayashi et al. (2022) examined VF fed with solar PV and wind energy systems for the production of lettuce, tomatoes, and wheat in Spain and Sweden. According to their study, freed farm area would only be obtained for producing lettuce, and with hypothetical improvements in the efficiency of current technologies such as solar PV systems, and artificial lighting. Both studies, however, considered the electricity requirements and disregarded other forms of energy used, such as direct use of fossil fuels in traditional open-field crop production. In another study, Rehman (2022) estimated the maximum number of levels of a VF fed with off-grid solar PV systems without additional land requirements. The study simulated the results for different locations and configurations, obtaining values of up to 3.5 floors, only considering energy requirements for lighting.

Water use efficiency: Water savings in VF might represent an opportunity in regions exposed to water scarcity (Kobayashi et al., 2022), which might also provide signals of their performance in terms of generation of wastewater. Graamans et al. (2018) compared water use efficiencies for hypothetical models of VF and greenhouses in Sweden, the Netherlands, and the United Arab Emirates (UAE), encountering consistent values for VF across different locations, which outperformed greenhouses. Potential reductions in water usage compared to greenhouses ranged from 28% in the UAE, to 95% in the Netherlands. Although the water use efficiency varies with the types of crops and design parameters, studies suggest ranges of 0.8 – 12 l/kg for high-controlled indoor environments such as hydroponics and VF; 1 – 24 l/kg for greenhouses; and 250 l/kg for open field crops (Barbosa et al., 2015; Graamans et al., 2018; M. Li et al., 2022; Martin et al., 2022).

Resource uptake and release of toxic substances: The material flows associated with VF may be outlined from existing studies addressing their environmental performance from a systems-thinking perspective (Li et al., 2022; Martin et al., 2019; Martin & Molin, 2019; Martin & Orsini, 2022; Martin et al., 2022) as suggested in Figure 3.

Figure 3. Material flows associated with vertical farming.



Source: The author.

The inputs of materials in VF vary with their design, depending on features such as whether development takes place in new or existing buildings (Lubna et al., 2022; Martin et al., 2022), the level of automation, and choices for lighting, growth media, packaging, and fertilizers. Regarding toxic substances, crop production in highly controlled indoor environments such as VF might eliminate the need for agrochemicals (Ramin-Shamshiri et al., 2018; Saraswat & Jain, 2021; Shao et al., 2022; Van Delden et al., 2021), although some authors suggest that indoor farming is not exempt from pests due to potential growth of fungus and arthropods (Avgoustaki & Xydis, 2020; Lubna et al., 2022). Van Delden et al. (2021) suggested eliminating the use of pesticides in VF by using beneficial organisms, strict hygiene measures, and non-chemical disinfection. Plant growth in VF relies on inputs such as seeds, growth media, and fertilizers. Regarding these materials flows, Li et al. (2020 and Martin et al. (2019; 2020) suggested replacing conventional fertilizers with nutrients obtained from shared flows with other processes (e.g., organic residues), although this might not have a significant impact on the overall environmental performance of VF. In contrast, the choices of materials for packaging and growth media might be determining.

Economically thriving, robust food value chains

Different economic indicators may signal the economic viability of VF, including the net present value, return on investment, break-even point (or period operating with no return on investment), and payback period. Existing studies providing economic estimations for VF are predominantly based on theoretical assumptions, and information on real VF cases might remain scarce. De Oliveira et al. (2021) and Lubna et al. (2022) suggested the need for further collaboration and data sharing among VF farmers to develop academic research that reduces uncertainty and business-related risks.

The estimated payback periods for VF vary widely across studies, from roughly one year, up to 15 years. Li et al. (2020) projected payback periods of 9 – 17 months, for a small-scale VF in Singapore built from standard containers, and considering hypothetical scenarios of waste valorization, market demands, and the possibility of selling the produce as organic. Zhang et al. (2018) estimated break-even points of 2 – 3 years, and payback periods of 7.5 – 15 years for hypothetical VF at a university. The results varied with various assumptions, such as the number of floors, types of crops, and profitability of the produce. Didenko et al. (2021) estimated a break-even period of 5 years, and a payback period of 15 years for a hypothetical VF located in the Russian Arctic that involved the construction of a newly built facility of 1000 m2. The authors suggested the need for expanding potential markets and scaling-up facilities to reduce investment and operational costs per unit of produce. Most of the operational costs of VF might be represented by power requirements, and labour-force (Kozai, 2019; Lubna et al., 2022; Milestad et al., 2020, Van Delden et al., 2021). From the consumer perspective, transport-related costs might be reduced depending on their location relative to intended markets (Rehman, 2022), although further study may be required to examine this from the producer's perspective.

Different studies suggest enhancing the economic viability of VF through decision making across the stages of planning, design, operation, and/or management. Some examples include reducing labour-related costs by implementing automated systems (Asseng et al., 2020; Van Delden et al., 2021), or taking careful consideration of the cost of land in cities to reduce potential investment and/or operational costs (Kalantari et al., 2018; Shao et al., 2022). Particular emphasis is found in strategies to ensure multifunctionality of VF, whether by combining various crops or offering additional services (Graamans et al., 2018; Lubna et al., 2022; Saraswat & Jain, 2021), or by implementing synergies with local and surrounding businesses within the concept of circular economy (Langemeyer et al., 2021; Van Delden et al., 2021). The marketability and profitability of the produce might also define the economic viability of VF (Lubna et al., 2022), and features such as their highly controlled environments and no use of pesticides might allow obtaining high-quality produce to enhance profitability (Saraswat & Jain, 2021; Van Delden et al., 2021). Further, SharathKumar et al. (2020) referred to the possibility of moving from GMOs to a concept of environmentally modified goods in VF, and Ramin Shamshiri et al. (2018) and Saraswat & Jain (2021) suggested that VF produce meets organic standards.

Just, ethical, and equitable food systems

Crop production in highly controlled environments and potentially reduced use of agrochemicals in VF might help mitigate ecosystem and population exposure to toxic substances. Further, a recent experimental study found higher nutrient values in watercress grown in VF compared to traditional crop fields in California and the UK (Qian et al., 2022). From the review of literature, claims on the potential role of VF in food security are often related to their potential to produce locally and therefore, to reduce the vulnerability of populations exposed to fresh food scarcity, especially in cities. Armanda et al. (2019) performed a literature review on Innovative Urban Agriculture including VF, suggesting that the information available to estimate their scalability and potential contribution to self-sufficiency remains insufficient.

Scaling-up farming in urban areas could introduce new dynamics into cities (De Amorim et al., 2019), and if VF are properly integrated into these dynamics their viability might be enhanced. Zareba et al (2022) suggested planning VF as multifunctional systems that offer further services to cities, such as greening the urban landscape, and gastronomy and recreational services. The possibility of creating VF synergies with local businesses and communities might depend on how this concept is perceived. According to Jürkenbeck et al., (2019) previous studies on urban farming demonstrated that purchase choices in urban areas are influenced by how *sustainable* these technologies are perceived to be. The authors performed a survey to understand consumer acceptance of VF in Germany, observing that acceptability varies with scale. Further, lower acceptance levels were found for small-scale VF, which were also associated with lower perceived sustainability levels. This is aligned with findings from Shao et al (2022) who studied the potential of increasing vegetable self-sufficiency in Shanghai by VF at the household level, encountering lower potential when public acceptance and preferences were considered. Al-Chalabi (2015) also interviewed actors from various sectors in the UK, encountering a perceived idea of hydroponic crops as chemical-based processes. Lubna et al., (2022) suggested the need for creating strategies of branding and consumer education, to enhance potential synergies of VF with local communities and businesses. The authors also suggested proper planning to ensure the availability of local skilled-labour force required to ensure optimal performance of VF, and to foster their role in local job markets.

Aims and priorities of sustainable food systems in Canada.

The Government of Canada provides strategic documents to guide decisions and actions towards sustainability. Some of these documents are specifically designed for the agri-food sector, while others encompass multi-sectorial strategies. While these documents are continuously updated, they are the result of extensive dialogues involving multiple stakeholders, providing insights into the aims and priorities of sustainably transforming food systems in Canada. Six federal-level instances were revised, including the Federal Sustainable Development Strategy – FSDS (2022 – 2026); Federal Sustainable Development Act (FSDA); Canada's 2030 Agenda National Strategy (2021); Greening Government Strategy (2020); Food Policy for Canada (2019); and Agriculture and Agri-Food Canada's Strategic Plan for Science (2022). Two documents currently under revision were also included, considering their relevance to this study: the Sustainable Agriculture Strategy and the Green Agriculture Plan. Consistently with the approach of this study, most strategic documents suggest addressing the sustainability of food systems in terms of desired outcomes. In most cases, sustainability concerns are expressed with a holistic approach that involves two or more societal scores. Emphasis is on the need to create resilient food systems, reduce vulnerability, and increased adaptation to climate change.

Among the societal goal *Clean and healthy planet*, most concerns focus on reducing GHGs and/or achieving a net-zero economy. In terms *of just, ethical, and equitable food systems, emphasis* is on food security, with a special focus on indigenous communities. Concerns related to *healthy, adequate, and safe diets* are expressed in terms of food systems' contribution to improving ecosystems and human health in Canada. For the societal score of economically *thriving, robust food value chains,* emphasis is on self-reliance on food, and on innovation in the agri-food sector. Although all areas of concern in Hebinck's sustainability compass are addressed in these strategic documents, no specific mention of the use of agrochemicals, or of cross-border spillovers (i.e., environmental impacts externalized to other countries) were found. Instead, other concerns regarding the sustainability of food systems in Canada include: i) Implementing nature-based solutions; ii) Establishing partnerships and synergies among sectors with circular economy strategies; iii) Increasing agricultural productivity; iv) Reducing food waste and/or responsible consumption; and v) Controlling new developments in new agricultural practices.

Discussion

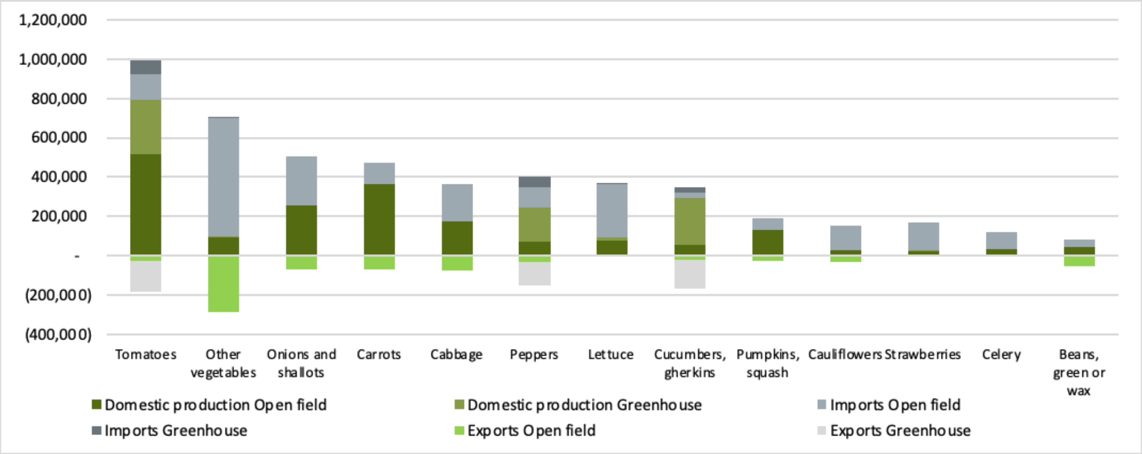
The potential opportunities and challenges of a food system's component or technology to contribute to its sustainability depends on its capacity to induce transformative changes towards reduced vulnerability and enhanced resilience. Accordingly, their implementation should enhance the ability of a food system to deliver its desired outcomes despite uncertainty or disruptions (Prosperi et al., 2016). From the review of literature, differing results among studies suggest plasticity in VF performance across the societal scores of sustainable food systems. Remarkably, most authors envision potential opportunities of VF based on scenarios that involve successful implementation of circular economy strategies, ensured profitability, and improved efficiency of related technologies. Meaning that this potential might depend on the viability of those scenarios. The opportunities and challenges of VF to contribute towards the desired outcomes of sustainable food systems might depend on each context, and on decision making across the fields of engineering (e.g., number of levels, size and type of building, lighting, heating and cooling, automation level), cultivation science (e.g., temperature needs, growth media, yield, time of lighting, media growth, and use of fertilizers), and management (i.e., strategic planning, types of crops required, and marketability of the produce). Further, the potential significance of each opportunity of VF to help sustainably transform a food system might differ by context. For instance, water savings might represent an opportunity where water scarcity is a threat, and local crop production might benefit populations isolated or exposed to shortages in fresh fruits and vegetables. The high energy requirements of VF, typically in the form of electricity, might pose challenges in locations facing issues of electricity continuity or prices, or where supply with low-carbon technologies is not feasible. In the context of Canada, and consistently to the aforementioned findings of Martin & Molin (2019) in Sweden, implementing off-grid REs might not lead to reduce GHGs as compared to grid-fed VF, where electricity is predominantly based on non-emitting sources. This may be the case in provinces such as Quebec, British Columbia, Manitoba, and Newfoundland and Labrador, where over 94% of the electricity is generated with REs and/or nuclear sources (CER, 2017). Potential water savings might represent an opportunity to improve food systems' resilience in regions potentially exposed to droughts, such as the Canadian Prairie Provinces (Tam et al., 2019).

Regarding the aims and priorities for the sustainability of food systems in Canada, the need for reducing GHGs is often emphasized in strategic documents. However, enhancing self-sufficiency with increased domestic production implies internalizing environmental spillovers (i.e., environmental impacts currently externalized to other countries), including resource uptake (i.e., water, energy and materials as suggested in Figure 3), and related GHGs. In light of VF dependence on electricity provision, reduced vulnerability from imports might be counteracted by dependence on continuous and affordable electricity. The multidimensional nature involved in the sustainability of a food system and of its components entails diverse value judgements, and trade-offs between sustainability goals (Bunge et al., 2022; Nilsson et al., 2016; Hebinck et al., 2021), meaning that there might not be solutions providing benefits without trade-offs and divergent perspectives for their desired outcomes. Examples of this include that VF may be regarded as nature-based solutions (Zaręba et al., 2021), while the concept might be arguably related to artificial environments; or cutting labour-related costs by implementing automated systems (Asseng et al., 2020; Van Delden et al., 2021), while enhanced synergies with communities and added value to local job markets might be desired. From the literature review, community and consumer acceptance is necessary to foster the viability of VF, which might be ensured with early involvement of communities in decision making. This requires special consideration provided that most strategic documents guiding sustainability in Canada emphasize the need to ensure food security for vulnerable communities. Remarkably, the types of crops produced in VF might define their viability. Hence, the desired types of crops to produce, and the purpose for this production (i.e., self-sufficiency, and/or domestic to international exports) must be clearly defined.

Theoretically, a wide range of crops may be grown in VF, and multi-crop production may be desired. However, this has an impact on their energy uptake and therefore, on the feasibility of VF, and further research is required. Current data and trends on the production, imports, and exports of fresh fruits and vegetables by province, similar to that at the country level provided in Figure 4 might inform early dialogues on the expectations of implementing these technologies in Canada.

> **Remarkably, the types of crops produced in VF might define their viability. Hence, the desired types of crops to produce, and the purpose for this production (i.e., self-sufficiency, and/or domestic to international exports) must be clearly defined.**
>
> – The author

Figure 4. Crop production, imports, and exports in open field and greenhouses in 2021 in Canada (metric tonnes). Data from Government of Canada (2023).



Source: Elaborated with data from Government of Canada (2023)

Since this study intends to inform dialogues on the role of vertical farming in sustainably transforming food systems in Canada, the analysis of findings from the literature review was complemented with a trade-off analysis, identifying potential opportunities and related challenges of VF regarding the desired outcomes of sustainable food systems. The results of this trade-off analysis are presented in Figure 5.

Figure 5. Trade-off analysis integrating opportunities and challenges for the desired outcomes of sustainable food systems.

🟩 Opportunities ▨ Challenges ⬛ Further considerations

Desired outcome:	Reduced GHG emissions	
Supply power requirements with grid electricity in provinces where most electricity is generated with non-emitting sources, such as Quebec, British Columbia, Manitoba, and Newfoundland and Labrador.		Consider future scenarios of electricity generation for current and enhanced policies in Canada.
Implement off-grid REs to supply power requirements	Obtain freed farm area (See [A]) Ensure the feasibility and availability of land to produce off-grid REs. Ensure continuity, consistency, and affordability of electricity [B]. Obtain an affordable fresh produce (See [C]).	Consider fluctuations in the hours of light/day, and potential presence of snow that might interrupt generation in off-grid PV systems. The use of electricity from off-grid solar PV might not result in reduced GHGs, depending on the local energy mix (Martin & Molin, 2019)
[C] Optimize the design and operational parameters to minimize the electricity uptake	Optimize yield, while obtaining fresh produce that is affordable [C], and of high quality in terms of nutritional value (See [D])	Consider the needs for the types of crops produced Consider potential synergies with surrounding businesses and activities to share flows of water, energy, and materials (See [E])
Reduce GHG emissions by establishing synergies with local businesses and communities (See [E])		This refers to GHGs related to the operation of VF. Net reduction of GHGs should consider both domestic emissions, and embodied in trade (See [F]).
Desired outcome:	Halted soil erosion; Sustained biodiversity conservation: Reduced use of toxic substances and of emissions of substances such as nitrogen and phosphorus	
[A] Obtain freed farm area	Optimize the design and operational parameters to increase yield (e.g., temperature; type, intensity, and duration of lighting; number of levels; density of crops), without compromising the quality and nutritional value of crops [D]. Ensure profitability for businesses (See [G])	Consider current scenarios of fresh fruit and vegetable sources (i.e., field + greenhouse + imports), as a benchmark to estimate net freed land area. A fair comparison considers total area requirements for crop production, and to supply the energy needed in various forms (e.g., electricity, use of fuels in open field). The possibility of obtaining a net freed farm area also depends on advances in technologies such as lighting and off-grid ERs.
Reclaim value of abandoned buildings.	Cost of land in cities might increase investment/operational costs.	Zoning in cities might be a constraint.
Reduce pressures upon soil, and foster biodiversity conservation with reduced use of agrochemicals	Obtain freed farm area (See [A])	Refers to environmental impacts both domestic and embodied in trade (See [F])
Desired outcome:	Sustainably managed water	
Reduce water usage and wastewater related to crop production	Higher water demand, associated to increased local/domestic production. Ensure availability and sufficiency of water [B].	Other technologies in controlled environments, such as greenhouses, might allow similar reductions in water usage. Consider water usage both domestic and embodied in trade, to establish a fair comparison (See [F])
Desired outcome:	Increased adoption of transformative business practices	
[E] Establish synergies with surrounding businesses and activities to share flows of water, energy, and materials.	Design feasible, resilient, and sustainable models of circular economy. Ensure availability and continuity of inputs [B] by proper planning shared flows of resources, and spare inputs.	Shared flows might help reduce operational costs, and environmental aspects (resource uptake, and waste) for all involved businesses
Desired outcomes:	Profits in food value chain adequately distributed; Stabilized commodity prices.	
[G] Ensure profitability for businesses. The prices of the produce from vertical farming might be comparable to premium products, such as organic certified.	Ensure the marketability of the produce by clear definition and dimensioning of the types of crops to produce and intended market(s) [H]. Offer fresh produce that is affordable [C], and of high quality in terms of nutritional value [D]. [E] Establish synergies with local businesses to reduce costs related to flows of energy and materials. Foster community and consumer acceptance [I]. [C] Optimize the design and operational parameters to minimize the electricity uptake Seek multifunctionality, by producing various types of crops and/or other services for the community [K]	Consider the requirements for organic certification by country [J]. Further research is needed on the feasibility of producing varied and profitable crops in vertical farming [L]
Obtain fresh produce that is affordable [C], and of high quality in terms of nutritional value [D].	The prices of the produce from vertical farming might be highly influenced by electricity and labour-related costs. The viability of vertical farming might depend on the marketability of the produce [H], which might also be influenced by consumer acceptance [I].	The possibility of obtaining stabilized commodity prices might depend on the markets of electricity and fertilizers, and on

	The prices of the produce from vertical farming might be comparable to premium products, such as organic certified [J].	proper dimensioning of the demand + offer of produce [H].
Desired outcomes:	Secured living wage and stability of employment; Just working conditions ensured; Equitable access to capital, knowledge, and technology achieved;	
Create local and continuous job opportunities in the agri-food sector	Ensure availability of local labor-force with the required skills and knowledge to operate the systems [M]. Balance automated and labour-based processes to ensure profitability for businesses [C], while providing value to local job markets.	Consider involving communities at early stages of planning [N]. Seek multifunctionality to allow providing services for the needs of the community [K]
Desired outcome:	Increased investment in agri-food research.	
Develop further research on producing varied and profitable crops in vertical farming [L] providing empirical data that is valid for the context of Canada. Make Canada a leader in research towards enhancing the role of vertical farming in sustainably transforming food systems.	Attain coordinated action between academia, governments, and industries, to direct investments in vertical farming research according to real needs to enhance the potential role of vertical farming in the sustainability of food systems in Canada.	
Desired outcome:	Reduced burden of foodborne diseases caused by biological and chemical hazards.	
Reduce the share of fresh food with GMO, and/or containing agrochemicals.	Design and maintain facilities to remain free of plagues	Procure bio-based fertilizers Implement strict hygiene measures, and non-chemical disinfection (Van Delden et al., 2021) Where the intended market involves exports, consider border requirements for agriculture products might involve the use of agrichemicals.
Desired outcomes:	Increased food security and nutrition; Increased share of population with a balanced energy intake; adequate nutrient intake; and adhering to the national food based dietary guidelines	
Produce fresh fruits and vegetables locally, in regions currently exposed to shortages. High-controlled environments might allow increased and consistent yields of fresh fruits and vegetables, year-round. Produce crops with high nutrient value in controlled environments	Ensure profitability for businesses [G], and affordability for consumers [C]. Ensure quality and nutritional value of crops [D]. Define and dimension the types of crops to produce and intended market(s) [H], aligned with current and future needs to ensure healthier diets.	Involve communities at early stages of planning [N] to foster potential outcomes related to improved diets.
Desired outcome:	Balanced trade openness; Shared food system externalities.	
	Environmental pressures currently externalized to other countries (i.e., impacts embedded in imports) to be assumed domestically. Potential increase of GHGs, flows of water, energy, and materials such as seeds, growth-media, and fertilizers to be acknowledged. Ensure proper dimensioning and planning to ensure continuous availability and sufficiency of resources [B].	Acknowledge the internalization of environmental impacts associated with increased domestic production [G]
Desired outcomes:	Protected nature´s contribution to people; Protected right to food.	
Increase self-sufficiency of fruits and vegetables locally [O], with potentially minimized land intensity.	Ensure the acceptability of VF facilities in regions where communities hold a close relation to the natural environment.	Involve communities at early stages of planning [N] to foster community and acceptance [I].
Reduce food waste in transport processes	Ensure the marketability of the produce by clear definition and dimensioning of the types of crops to produce and intended market [H].	
Desired outcome:	Increased food security and nutrition; Self-reliance in food achieved; Protected right to food.	
Increase self-sufficiency of fruits and vegetables [O]	For each region, define if implementing vertical farming seeks to increase domestic to local self-sufficiency, and/or if the intended market relies on exports. Define and dimension the types of crops to produce and intended market(s) [H], aligned with self-sufficiency needs. Develop further research on the feasibility of producing varied and profitable crops in vertical farming [L] providing empirical data that is valid for the context of Canada. Where increased self-sufficiency is desired in remote regions, ensure availability and sufficiency of resources [B], and of skilled labour-force [M].	Acknowledge the internalization of environmental impacts associated with increased domestic production [G]. Consider the potential role of vertical farming in the planning of cities.
Reduce vulnerability related to dependence on imports.	Potential increased vulnerability related to dependency on water, energy, and materials (e.g., growth media, fertilizers, seeds). Ensure sufficiency, affordability, and continuity in the availability of resources [B]	

Recommendations

The rationale of VF might be similar to that of technologies such as solar PV systems, which may contribute towards specific desired outcomes of sustainability, but also counteract others. Therefore, clear definition of priorities in terms of the desired outcomes of sustainable food systems in Canada might alleviate the complexity involved in decision making, facilitating trade-off analyses in multistakeholder dialogues. A necessary step to provide insights into the direction that further research on VF should take in Canada, is to define the purpose for their implementation in each context and/or region, signaling the types of crops to produce, and intended markets. The use of modelling tools to different combinations of configurations, locations, and scenarios of VF, might allow planning in the direction of the desired outcomes of sustainability, while reducing associated risks from the feasibility stage. Different authors have developed models for decision making, specifically designed for VF. Didenko et al. (2021) developed a model to predict profitability using system dynamics simulation; De Oliveira et al. (2021) developed a decision support system (DSS) to provide early information on the types of crops that may be produced, ensuring the adequacy and profitability of the produce. Li et al. (2020) proposed a decision-making model for simulating different combinations of types of crops, energy supply, types of venues, and locations. Martin & Orsini (2022) proposed guidelines to perform LCAs specifically designed for VF. Provided clear definition of the purpose of implementing VF in Canada, and of their expected role in the sustainability of food systems, further research addressing their sustainability should be performed adopting a system-thinking perspective to provide a comprehensive vision of their potential outcomes.

Conclusions

The potential opportunities and challenges of VF to contribute to the sustainability of food systems are relative to multiple factors associated with their planning, location, and design. The discussion on their role in sustainability should be addressed in multistakeholder dialogues on their potential trade-offs for the desired outcomes of sustainable food systems, supported with further research applicable for the varied contexts of Canada. The results of existing studies addressing the sustainability of VF often apply to specific crops, designs and locations, and further research is needed to attain more generalizable results. The findings of this study suggest that future research on the sustainability of VF should consider their potential multifunctionality, which might also define their performance across all sustainability dimensions. The energy uptake and operational costs of VF are largely defined by the type of crops produced, and by the marketability of the produce. Hence, defining potential markets for the produce is a necessary step to provide insights into the direction that further research should take.

Strategic documents towards the 2030 SDG agenda in Canada express the aims of sustainability applied to food systems in terms of desired outcomes that encompass two or more dimensions of sustainability. Provided the complexity involved in potential trade-offs across multiple areas of concern in sustainability, prioritizing these desired outcomes might be key for the rationale of implementing VF in the different contexts of Canada.

The review of literature and trade-off analysis performed in this study suggests potential opportunities of VF to help sustainably transform Canada´s food systems. Although there are also challenges associated to these opportunities, enhancing their potential contribution to more sustainable food systems might be a matter of proper planning, further research, and sustainability management. Further, producing crops in highly controlled environments requires ensuring continuous availability of inputs such as seeds, fertilizers, water, and electricity. Provided that sustainability involves enhanced resilience of food systems, and reduced vulnerability of populations with food security, the availability of these resources must be ensured. Further, increased resource uptake and domestic GHGs should be acknowledged as potential trade-offs of increasing crop production, either locally, or domestically.

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