The Next Course

Expert Panel on
Atypical Food Production Technologies
for Canadian Food Security

CCA | CAC

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COUNCIL OF CANADIAN ACADEMIES
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The Expert Panel on Atypical Food Production Technologies for Canadian Food Security would like to acknowledge the First Nations, Inuit, and Métis peoples who have been, and continue to be, stewards of the lands now known as Canada.

The Council of Canadian Academies’ (CCA) offices in Ottawa are located on the unceded traditional territory of the Anishinaabe Algonquin People, who have cared for these lands for millennia.

The CCA is committed to reconciliation and honouring Indigenous sovereignty. Through our work in providing evidence for decision-making, we at the CCA recognize that a wide range of knowledges and experiences contribute to building a more equitable and just society. We encourage all who engage with our work to further learn about and acknowledge the past and present context of the land now known as Canada and of the Indigenous Nations and Peoples who steward it.

Expert Panel on Atypical Food Production Technologies for Canadian Food Security

Expert panel members serve as individuals and do not represent their organizations of affiliation or employment. Each panellist was selected for their expertise, experience, and demonstrated leadership in fields relevant to this project.

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Message from the Chair

Working within the global food and agriculture system is both exciting and challenging. On one hand, people rely on time-honoured techniques and relationships to provide the foods they know and trust. On the other hand, humanity has always invested heavily in agri-food technologies, from irrigation and crop rotation to genomics and controlled environments. We are in a race to produce more food, with fewer inputs, while respecting cultural needs and ecological limits. Food is many things, but it is never boring.

Food production around the world is facing a range of interrelated and compounding challenges, including a changing climate, increasing energy demands, and geopolitical instability. Canada is rising to these challenges and is already a world leader in both agricultural technology and the innovations needed to support our food system. Yet we are not immune to emerging threats to the continued stability and sustainability of our food system.

Actively growing our innovation portfolio in agri-food is needed if Canada is to be resilient in the face of these threats. Canada must lead. In this report we discuss "atypical" food production technologies, with the understanding that some of these technologies will become the typical tools of tomorrow's farmer.

Atypical food production technologies have an important role to play in adapting the food system to meet the realities of today and the future. Innovations in the field of indoor growing of fruits and vegetables have the potential to allow for high-quality produce to be grown in new locations, including urban centres and Canada's northern regions. At the same time, innovations in protein production—an area of existing Canadian leadership—hold promise for supporting a more diversified protein portfolio that better meets the needs of consumers.

Alongside Canada's existing food production methods, these atypical production technologies have the potential to increase the diversity of the food system, providing greater resiliency overall. As an agri-food superpower, Canada has the potential to be a world leader in these new methods of food production but is currently falling short. Food security is achieved by investing in a portfolio of food and agriculture industries; in food systems, diversity is strength. Canada needs to be a living laboratory where the world's food future is born.

Understanding the potential benefits, drawbacks, and barriers to implementation of these new atypical food production technologies is instrumental for guiding developers, investors, decision-makers, and the public in making informed choices moving forward. *The Next Course* contributes to this understanding by introducing a variety of atypical food production opportunities for meeting the challenges facing food production over the coming decade. This report is not meant to be exhaustive, but rather to introduce a selection of promising technologies that are far enough along in development that scaling is possible with proper investment.

I want to thank my fellow panellists for their hard work throughout the assessment process. Their experience and deep knowledge fostered insightful discussions on this difficult question. The panel's hard work has led to what I believe is a high-quality and important report that can inform decision-makers on one key dimension of the future of food production in Canada.

Sincerely,

Lenore Newman
Chair, Expert Panel on Atypical Food Production Technologies for Canadian Food Security

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This report was reviewed in draft form by reviewers selected by the CCA for their diverse perspectives and areas of expertise. Their anonymized submissions were considered in full by the expert panel. Reviewers were not asked to endorse the conclusions, nor did they see the final draft before its release. Responsibility for the final content of this report rests with the expert panel and the CCA.

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Executive Summary

Innovation in food production can ensure the resiliency of Canada's food system in the face of increased demand for food and the unpredictability of climate change.

Canada is a world leader in agri-food with the potential to play a critical role in the changing nature of the global food system. Directly linking food production to food security, however, is challenging. Food security is complex, relating to the availability, accessibility, and utilization of food, as well as the stability and sustainability of the food system overall. The agency of consumers to make decisions about the food they eat is also critical. Food production can only impact some of these dimensions and, in isolation, changes in production will not drastically impact food security in Canada. Furthermore, while Canada is home to significant levels of food insecurity, particularly among racialized households and in the North, the root causes are a range of social factors that may be external to agricultural production, such as poverty. Having said this, threats to agricultural production are impacting the stability and sustainability of the country's food system and affecting food security. These threats include climate change, supply chain disruptions, finite environmental resources, and challenges maintaining production levels and economic viability. The future of food and agriculture cannot continue on the same path, and increased diversity through innovation in the food system is required to ensure that people in Canada can access the food they want and need. Atypical food production has a role to play in increasing production and productivity while strengthening the resiliency of the food system in parallel with other forms of agriculture as well as Indigenous food practices.

Advances in controlled environment agriculture (CEA) have the potential to build on Canadian strengths and enable local production of produce when driven by communities.

CEA allows for year-round growth of fruits, vegetables, high-value plants, and mushrooms indoors, including in locations ill-suited for field-based agriculture. Importantly, CEA has the potential to provide stability and control over crop production, building resilience to increasingly frequent and severe weather events. Canada has a long history with greenhouses, but advances in CEA enable entirely indoor farming options and hybrid systems that offer complete control over the growing environment, regardless of outdoor conditions.

With current technologies, however, there are trade-offs between costs and environmental outcomes that can impact sustainability. While in some cases CEA uses fewer inputs (e.g., water) and less land to produce food compared to conventional field-based growing, the method also requires significant amounts of energy. The source of this energy (e.g., fossil fuels, renewables) dictates whether carbon savings will exist relative to conventional production. Moreover, the cost of energy for the construction and operations of CEA systems can limit economic feasibility. The most promising technological advances in CEA are those seeking to improve productivity and reduce environmental impact while simultaneously balancing costs, particularly those related to energy use. This includes advances in covering materials, artificial lighting, renewable energy production, climate control, nutrient and water delivery systems, and sustainable pest management.

The vast geography, and the variable climatic and social conditions across Canada mean that no single technological advancement in CEA is best suited for improving food security in all locations. For instance, an off-grid community might value a container farm's reliability and mobility above slightly enhanced efficiency. The limited variety of foods that can currently be grown indoors is also an important constraint, both for food security and economic viability. Critically, the appropriateness of CEA in Indigenous communities can only be determined from an understanding of local needs and capacities to ensure alignment with food security and sovereignty goals set by the communities themselves.

> Technological advancements that diversify Canada's protein portfolio may support innovation and increase food system resilience and choice for consumers.

The changing landscape around protein consumption, including shifting consumer preferences and diversification, suggests a need to consider the role of atypical protein production technologies. Canada is a leader in conventional protein production—including livestock farming and ranching, and farming of plant protein sources—and advancements in atypical production can continue this legacy while increasing the sector's resilience. Opportunities for innovation exist across a variety of protein sources: through improvements to existing, small-scale markets and operations (seaweed), innovations in food ingredients and processing (plant-based alternatives, precision fermentation), and the establishment of entirely new methods of producing animal-based protein (cultured meat). The contributions that atypical protein production technologies could make toward food security would be indirect and limited to improvements to sustainability and the diversification of the industry. At the same time, leadership on emerging technologies, such as those related to cellular agriculture, could support innovation and develop expertise in globally relevant fields.

The success of atypical food production operations depends on the availability of local infrastructure, skills and labour, as well as a supportive policy environment.

Regardless of operation size, food production depends on local resources; both CEA and atypical protein production facilities depend on access to reliable energy, water, and internet infrastructure, for example. In the remote regions of Canada—some of the most food insecure—these services can be unreliable and expensive, creating a substantial barrier to establishing and maintaining operations. Access to labour and the needed skills is a challenge in food production more broadly, but may be exacerbated for atypical production due to the requirement for different and potentially broader skillsets. The availability and cost of labour, land, utilities, and logistical infrastructure will impact sustainability both for commercial and non-commercial producers.

The regulatory environment can create challenges for atypical food production systems because of the novelty of the associated products and processes. For example, safety regulations may need to adapt to account for differences between atypical and conventional production methods. There are also opportunities to use policy to enable and encourage growth in atypical production, such as zoning reform to support CEA in locations where conventional farming is not allowed. Coordination across the policy landscape is needed to ensure initiatives meet their goals and do not create new barriers. Considering community needs and goals is important for all policy development but is particularly essential for Indigenous communities. A given policy (or technology) developed in isolation from the community where it will be applied will not be successful in achieving its goals.

Innovation in and adoption of supporting technologies are critical to ensuring the economic viability and environmental sustainability of atypical production methods.

Beyond the core technologies underpinning atypical food production, several enabling technologies can support the sustainability of operations by increasing productivity and thereby profitability. For example, genomics can greatly impact CEA by enabling the development of variants tailored to the specific conditions of indoor growing, improving yields and expanding the range of foods that can be grown. There are also opportunities for targeting foods or variants with greater nutritional value or cultural significance. Digital technologies, and AI in particular, provide opportunities to bolster production and efficiencies across food production operations. The next wave of smart agriculture will be driven by AI, and recent advances suggest a substantially expanded scope for its application beyond simply completing narrow tasks. Amid the ongoing digitalization of agriculture, the fact that technologies are inherently embedded into atypical production underscores the importance of identifying avenues for effective and sustainable integration of digital technologies and AI.

Panel reflections

Moving forward, atypical food production technologies may depart from the conventional understanding of how food is produced, and a better knowledge of the benefits, drawbacks, and consequences—both intended and unintended—will be instrumental in guiding researchers, developers, investors, decision-makers, and the public in making informed choices. Atypical food production technologies hold promise for increasing food production and productivity while diversifying and increasing the resilience of food systems in Canada. Still, no single technology or type of facility will meaningfully impact food security per se, particularly on a national level. Geography and cultural context are critical, as technologies that may improve stability or sustainability in certain locations will not in others, without significant resources. Furthermore, many technological advancements in atypical production will not progress or achieve their stated goals without adequate enabling technologies and conditions, particularly access to renewable and affordable energy sources, and the needed knowledge and skills. Critically, a diverse food system, including both conventional and atypical production methods, is key to improving resilience in the face of future challenges.

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Introduction

To secure the future of food in Canada, there is a need for a broad, multifaceted strategy, of which technological advances in food production—particularly those advancing the sustainability of local, year-round food production—could be one part. In a desire to understand the role that atypical food production technologies may play in helping to support food security in Canada, the National Research Council of Canada (NRC, hereafter "the sponsor") asked the Council of Canadian Academies (CCA) to convene an expert panel tasked with examining the following question and sub-questions:

What areas of scientific and technological advancement (and related investment) in atypical food production[1] will most contribute to Canada achieving national food security within the next two decades?

- Taking into consideration the socio-economic benefits and challenges, what are the most viable technological solutions for sustainable year-round food production in Canada, including in remote and isolated locations with limited existing infrastructure?
- What social and economic factors may accelerate or hinder the development and adoption of these technologies, and what type of supporting ecosystem (and related investment) is required to address these factors?
- Given their present level of technology and commercial readiness, what are the economic constraints on adapting and implementing atypical food production methods at a meaningful scale (> 200 people)?

To answer the charge, the CCA assembled a multidisciplinary panel[2] (the Expert Panel on Atypical Food Production Technologies for Canadian Food Security, hereafter "the panel") with backgrounds and expertise in engineering, agricultural sciences, food security, agricultural economics, agricultural policy, and food production in rural, remote, and Indigenous communities. The panel

1 For example, indoor farming, vertical farming, controlled environment agriculture, digital/predictive analytics, and crop design, among others.

2 To ensure the integrity of the assessment process, panel members disclosed to the CCA and fellow panellists any conflicts of interest—actual, foreseeable, or perceived—relevant to the issues being discussed, to manage these transparently. Panellists also abided by a confidentiality agreement and code of conduct designed to support an environment that fostered effective and respectful deliberations, was conducive to the free exchange of knowledge, and supported the assessment of evidence.

included members with experience in academia, industry, communities, and government. The panel met several times virtually and three times in person over a period of 12 months to collect and review evidence and to deliberate on its charge.

At the beginning of the assessment process, the panel met with the sponsor[3] to gain an understanding of the charge and confirm which issues were in and out of scope. The sponsor noted that the panel was free to examine any type of atypical food production, although they requested a particular focus on technologies that enabled local, year-round production. Field-based agriculture, and livestock farming and ranching were to be considered out of scope. Importantly, the sponsor also acknowledged that technologies alone will not solve food insecurity and its underlying social and historical causes in Canada, but they expressed a desire for the panel to consider what aspects of food security could (and could not) be supported by atypical production technologies. While the charge articulates a focus on year-round production at a scale to support more than 200 people, the panel chose to instead consider technologies suited to a community-level scale, recognizing that communities come in a wide variety of sizes and contexts.

1.1 Interpreting the charge

From their earliest discussion, the panel struggled with how to fulsomely answer the charge while staying within its confines. The food system is a complex entity, but the charge questions limited the panel's analysis to one small slice of a single component, namely production (Figure 1.1). This limitation restricted the panel's ability to explore the interconnectedness of the various pieces within the food system, as well as its connections to other global systems (e.g., ecological) (Clapp *et al.*, 2022). Put simply, changes in food production will have a considerable impact on the other elements of the food system and vice versa. Although the broader system is not explored in depth in this report, the connections between production and the other components (e.g., processing, distribution) are critical considerations for any policy or initiative that seeks to impact food security. Additionally, the panel notes that atypical food production technologies (Box 1.1) encompass only a narrow slice of food production overall.

3 As part of CCA's process to maintain panel independence, sponsors do not appoint panel members, nor do they engage with the panel during the assessment development process, with the exception of the panel's first meeting, when the sponsor is invited to present the charge and answer any panel questions.

The *Federal Sustainable Development Act* notes that “sustainable development is based on an efficient use of natural, social and economic resources and the need for the Government of Canada to integrate environmental, economic and social factors in the making of all of its decisions” (GC, 2020a).

Technological and other innovations also have considerable potential to improve the sustainability of all types of production, including conventional agriculture (field crops and livestock farming) and traditional practices within Indigenous food systems (e.g., hunting). While the panel considers only atypical production methods in this report, they emphasize the importance of all production methods for meeting the needs of people in Canada and ensuring diversity in the food system, as this is essential to ensure resiliency.

Box 1.1 Defining atypical production

The term *atypical production* is ambiguous given the constant evolution of agriculture. Based on discussions with the sponsor, in combination with their own expertise, the panel chose to define atypical food production technologies as those that enable precise control over food production through the manipulation of environmental factors. For fruit and vegetable production, atypical technologies are defined as those that enable the growing of non-field crops through controlled environment agriculture (CEA), controlling factors such as light and temperature. Notably, some types of controlled environments, such as greenhouses, have been in use for centuries. Therefore, for this report, the panel considers atypical advances in greenhouse technologies beyond those in wide operation today, alongside other indoor farming types, such as vertical farms and container farms. For protein production, atypical methods are those that diverge from existing field-based sources (e.g., lentils), aquaculture, and conventional livestock farming and ranching practices. Atypical protein production encompasses protein sources that are emerging in Canada, including new plant-based protein sources and cellular agriculture technologies, defined as “the field of growing agricultural products directly from cell cultures instead of using livestock” (Khan, 2022).

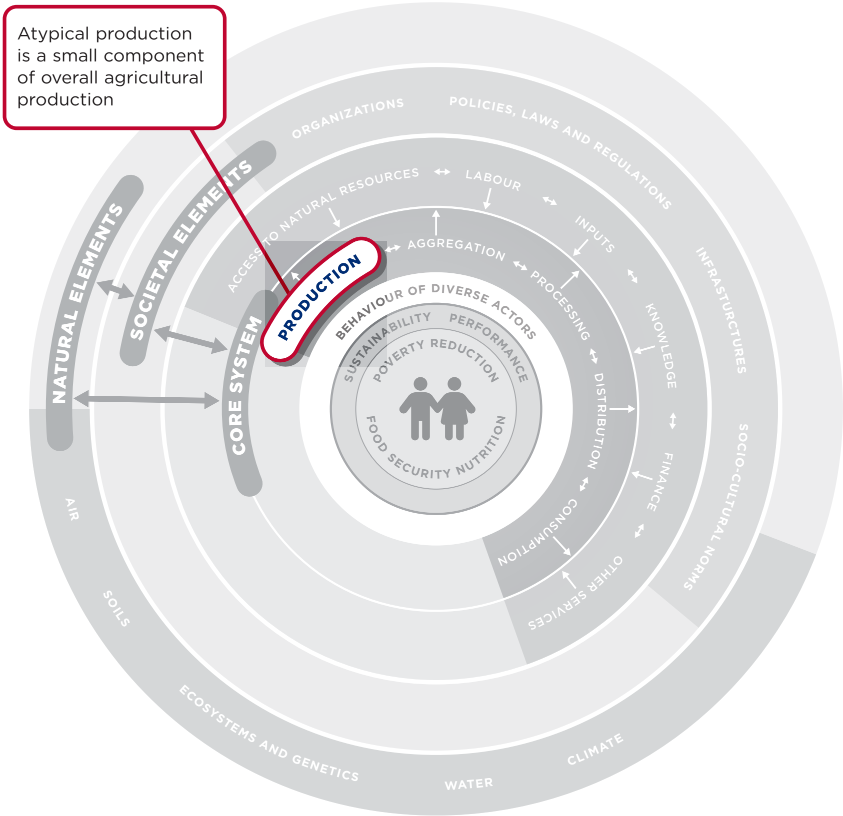


Figure 1.1 Production in the food system wheel

The food system wheel demonstrates the complexity of food security. The core food system contains several interconnected elements supported by a range of activities and services. Societal and environmental elements further influence the system. This report considers only a small slice of a single component in the core food system (atypical production), but the panel emphasizes that all elements within the food system are interrelated and contribute to food security.

After coming to an agreement on the technological categories to consider in their assessment, the panel deliberated at length on the relationship between food production technologies and food security. As noted, increasing the production of food in isolation will not translate to greater

> Increasing the production of food in isolation will not translate to greater food security.

food security. The panel noted that any benefits related to increased food production would not directly help Canada's most food-insecure populations without specific policy interventions. Furthermore, the mere existence of a promising technology does not guarantee increases in production, as sufficient investment, supporting policies, and infrastructure are required.

In discussion with the sponsor, the emphasis was placed on advancing local production, with a specific focus on remote, isolated, and Indigenous communities. Importantly, *local* is a subjective term with no universally accepted definition. For example, some may consider *local food* to have been created within the bounds of their communities or cities, while others consider local to encompass whole regions or provinces (Charlebois *et al.*, 2022). The panel also noted that there are inherent biases associated with the term local and emphasizes that sustainable food and local food are not equivalent (Stein & Santini, 2022). For example, food produced locally may or may not have a reduced carbon footprint as compared to food that must be transported to communities (see references in Stein & Santini, 2022). Regardless of the scale, the inclusion of regional, local, and cultural contexts into strategies and policies is needed if the deployment of novel technologies, including those related to local food production, is to be successful and just.

The concept of the *just transition* recognizes that rapid technological change is inherently disruptive and requires efforts to avoid negative consequences (Lee, 2022).

The panel therefore recognized that linking atypical production technologies and food security requires a focus on the technologies that can support environmental, economic, and social factors that would enhance the overall strength of Canada's food system. Through this lens, the panel considered broader guiding questions to aid and focus their analyses. For example, considering which atypical production technologies could have a positive impact by:

- reducing the environmental footprint of food production;
- making food more affordable for people in Canada;
- producing more food for local markets or export;
- supporting innovation and expertise (including for export); and
- supporting job creation (including for new farmers).

The panel's analysis is based on a review of various sources of evidence, drawn from peer-reviewed publications, publicly available government data, and relevant grey literature. Semi-structured interviews were used to supplement published evidence, particularly as it relates to on-the-ground challenges faced by practitioners using CEA technologies beyond the proof-of-principle stage. The expertise and experiences of panel members were a critical source of evidence, as were the learnings and insights that came from the discussions at panel meetings.

1.2 Relevant context

The agricultural production sector is economically important for Canada—through wealth creation and employment, for example—but it is also essential for providing food to people across the country and around the world. The primary agriculture sector is strong yet at the same time, the country is not fully food secure, with many people unable to access the food they want and need. In this section, the panel examines these issues. First is a brief introduction to the factors that define food security, followed by an overview of food insecurity in Canada, with a particular focus on the people and communities that are most food insecure. Secondly, the panel briefly considers domestic food production, demonstrating the significance of agriculture to the economy, as well as Canada's notable role as a net exporter of many types of food.

1.2.1 Food security in Canada

Food security relates to many factors beyond the availability of food

Food security is multifaceted and is defined by the FAO as "a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO *et al.*, 2022). Ensuring food security entails considering all elements of the food system (Figure 1.1) as well as the connections among these components. As such, there are several dimensions encompassed within the concept of food security (Ericksen, 2008; HLPE, 2020; FAO *et al.*, 2022; Harper *et al.*, 2022). These include the *availability* (encompassing production, distribution, and exchange); *accessibility* (encompassing allocation, affordability, and preferences); and *utilization* (encompassing social value, nutritional value, and safety)[4] of food. The overarching dimensions are the *agency* of consumers to make choices over the food they eat and participate in the governance over food (e.g., having a say over what produce is grown in the community); the *stability* of the food system (e.g., resilience to severe climate events); and the *sustainability* of the food

4 Some definitions of utilization include food allocation within a home and "variation in the extent to which the nutrients in food are able to be absorbed and metabolized by individuals within households" (Jones *et al.*, 2013).

system, namely its ability to support food security today in ways that do not compromise the environmental, economic, and social bases of food security for future generations.

Food security is complex and difficult to measure

The complexity of food security makes it difficult to quantify and measure on both an individual and collective basis. Some of this difficulty stems from the diversity of relevant scales. For example, food availability often relates to the national or regional scale, while accessibility pertains to the household and utilization to the individual. The place-based nature of food systems adds another critical layer of complexity, particularly relevant in the Canadian context, which has an incredible diversity of types of communities across a vast geographic area.

Because of these challenges, analyses considering the state of food security of individuals will instead often consider the measurement of food *insecurity*, which is defined as the "inability to acquire or consume an adequate diet quality or sufficient quantity of food in socially acceptable ways, or the uncertainty that one will be able to do so" (HC, 2020). This definition illustrates that food insecurity is a social problem driven by various factors outside of agricultural production, such as poverty and debt (Li *et al.*, 2023). While food insecurity is a widely used and valuable metric, it is important to keep in mind that food security is broadly defined and includes non-financial barriers, such as challenges in acquiring adequate nutrition or culturally appropriate food.

There are substantial numbers of food-insecure people in all regions of the country, with the highest occurrence in the North

Statistics Canada data from 2021 demonstrate that almost 18% of families[5] in the provinces[6] experienced food insecurity at some point in the previous year, affecting approximately 6.9 million people across Canada. Of this group, 1.9 million people (5% of families in Canada) were considered severely food insecure, "missing meals, reducing their food intake and, at the most extreme, going days without food" (Uppal, 2023). Provinces with the lowest rates of food insecurity are Quebec (14%) and British Columbia (17%), with the highest rates in Newfoundland and Labrador (23%), New Brunswick, and Alberta (both 22%). In terms of large urban centres, rates of food insecurity are highest

5 Families are defined as "economic families and unattached individuals living in households" (Uppal, 2023).

6 At the time of its publication, data from the Canadian Income Survey did not include information from the territories and therefore could not be included in Uppal (2023).

in Edmonton (21% of the total population) and Toronto and Calgary (both 20% of the population) (Uppal, 2023). However, these provincial data exclude people living on reserves or in other Indigenous settlements, those residing in institutions, or those in extremely remote regions; these are all groups that are known to be highly food insecure (Li *et al.*, 2023).

Data from the territories illustrates that rates of food insecurity are higher in the North. Data from the 2019 Canadian Income Survey included territorial data and demonstrated that a higher percentage of people face moderate or severe food insecurity in the territories compared to other regions of Canada (Uppal, 2023). This can be linked to the high cost of food. The North is largely dependent on southern food production systems, and high transportation, storage, and distribution costs make market foods expensive (CCA, 2014; Rall & LaFortune, 2020). Research from the provinces demonstrates that communities more than 50 km away from major urban centres are subject to food costs 2–3 times higher than in urban centres, but inflated food costs are even more severe in remote, fly-in communities (FNFNES, 2021). Food insecurity is particularly acute in Nunavut, where almost half the population is moderately or severely food insecure (Caron & Plunkett-Latimer, 2022). The rate of food insecurity among Inuit is linked to a range of interrelated factors, including poverty, high cost of living in the North, climate change, and policies and food systems based in colonialism that are ill-suited to Inuit communities (ITK, 2021). While climate change will create new challenges for food security across Canada, the North may be at particular risk as the effects of a changing climate are being felt more acutely in the northern regions of the country (Box 1.2).

Box 1.2 Climate change and food insecurity in Canada

Climate change contributes to food insecurity in many ways, including when weather events disrupt food supply chains, which increases local food prices and creates adverse nutritional effects (Harper *et al.*, 2022). Research also suggests that extreme weather events, more common as a result of climate change, have a negative and statistically significant influence on growth in the efficiency of agricultural production (Steensland, 2022). Furthermore, the effects of climate change on food

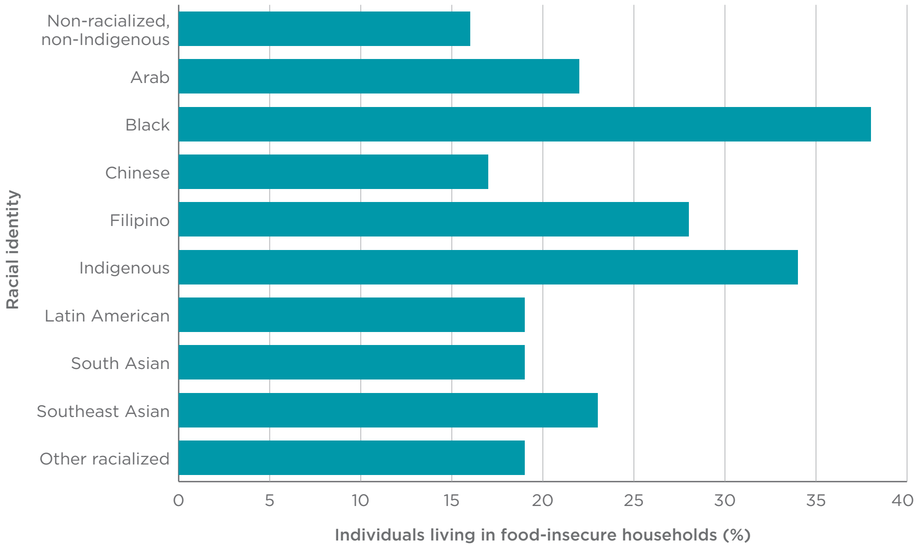
(continues)

(continued)

insecurity are unevenly distributed, with the greatest impact on Indigenous Peoples and those living in northern regions. Even if warming temperatures and longer growing seasons positively impact northern agriculture, climate change will negatively affect the safety and longevity of winter access roads, which can further increase food prices by limiting the transportation window (Rall & LaFortune, 2020). The distribution of effects varies and depends on the specific social, cultural, environmental, and economic situations and inequities of different communities. Disadvantaged populations who are food insecure are, in turn, more vulnerable to other climate-related health risks, which can further hinder efforts to protect and adapt communities to climate change (Harper *et al.*, 2022).

Rates of food insecurity are highest for people who identify as racialized, with Black and Indigenous people most negatively impacted

The rates of food insecurity are higher for racialized populations as compared to non-racialized (and non-Indigenous) populations (Figure 1.2). Based on provincial data, people who identify as Indigenous or Black are most negatively affected, with over a third of families experiencing some rate of food insecurity (Uppal, 2023).



Data source: Uppal (2023)

Figure 1.2 Percentage of individuals living in food-insecure households in the provinces by racial identity (including Indigenous status)

People who identify as non-racialized and non-Indigenous were the least likely to be living in food-insecure households in the provinces in 2021, whereas people who identified as Black or Indigenous were most likely. Notably, these data do not include Indigenous people living on reserves and people in the territories.

Data related to Indigenous people living on reserves also demonstrate that high levels of food insecurity are prevalent in these communities. For example, the First Nations Food, Nutrition and Environment Study conducted surveys to measure the ability of on-reserve households to purchase market foods and access country foods; the results demonstrated that 48% of households were food insecure (FNFNES, 2021). Food insecurity is also high in Inuit households, a situation which has been identified as one of Canada's longest-lasting health crises (ITK, 2021).

Food sovereignty and food security of Indigenous Peoples in Canada is based on a range of interconnected factors that include gender, place, and colonialism

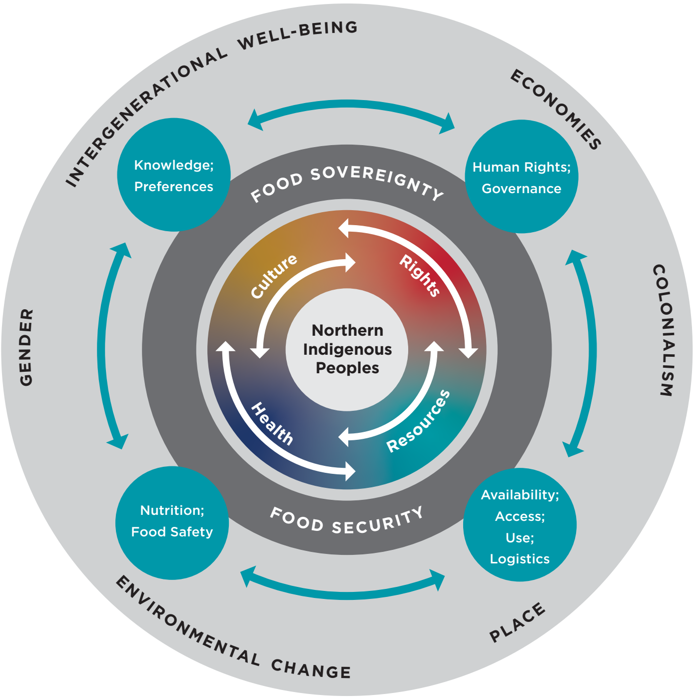
The concept of food sovereignty was initially proposed in 1996 at the World Food Summit by the global peasant movement *La Via Campesina* (Nyéléni, 2007). Food sovereignty differs from food security by calling for the recognition of "food as a fundamental right of all peoples" and the identification of food as "the common ground, starting point and guiding theme for achieving economic, social and political justice" (Nyéléni, 2007). This definition emphasizes food's role in strengthening communities, ecosystems, and economies. For example, the Qikiqtani Inuit Association explain that Inuit food sovereignty entails:

- "the right to healthy and nutritious food;
- the right to culturally appropriate food;
- the right to food harvested through ecologically sound and sustainable methods as guided by the Nunavut Agreement and wildlife management regiment; and
- the right to access wildlife in ways that empower communities and stimulate local economies."

(QIA, n.d.)

The authors further note that the concept, as it relates to Inuit, encompasses "Inuit knowledge, language, culture continuity and community self-sufficiency" (QIA, n.d.). This underscores that understanding both food security and food sovereignty in Indigenous communities requires consideration of the broad context of which food is a part, as well as recognition of the connections between food systems and other sociocultural dimensions, including gender, place, and colonialism (Figure 1.3). The context is unique for each community and is fluid, evolving with time.

Colonialism is a powerful contributor to the food insecurity of Indigenous Peoples across Canada as its foundation lies in separating Indigenous Peoples from land and the resources it provides (Joseph & Turner, 2020). The reserve system, for example, physically separated Indigenous Peoples from their traditional food and harvesting areas (Turner *et al.*, 2013; Joseph & Turner, 2020; Joseph, 2021) at the same time as pressure was applied to follow Western agricultural practices (Gov. of BC, 1875 as cited in Joseph & Turner, 2020). Indigenous scholar Jeff Corntassel (2012) describes the revitalization of traditional foods and the community role around food systems as acts of resurgence for Indigenous Peoples. Put another way, they are everyday practices that can be linked to decolonization of a community. The belief that the government and private sector are the only ones able to solve problems to do with food in Indigenous communities has been described as "colonial paternalism" (Sumner *et al.*, 2019); moving forward, care must be taken to avoid repeating colonialist patterns and ways of thinking.



Adapted from: CCA (2014)

Figure 1.3 Conceptual framework of the Expert Panel on the State of Knowledge of Food Security in Northern Canada

One example of a framework to conceptualize food sovereignty and security in northern Canada. The wheel illustrates the complexity of the relationships that affect food sovereignty for Northern Indigenous Peoples.

1.2.2 Food production in Canada

The agri-food system is a key contributor to the Canadian economy

The agriculture and agri-food system[7] in Canada employed 2.3 million people in 2022 while generating about 7% ($144 billion) of Canada's gross domestic product (GDP) (AAFC, 2024). Of that, over $36 billion stems from work taking place "within the boundaries of a farm,[8] nursery or greenhouse" (defined

7 The agri-food system is an integrated supply chain that includes: primary agriculture, food retailers and wholesalers, food service providers, and food and beverage processors (AAFC, 2024).

8 Since the 2021 Census of Agriculture, Statistics Canada has defined a farm as "a unit that produces agricultural products and reports revenues or expenses for tax purposes to the Canada Revenue Agency" (StatCan, 2022).

as *primary agriculture* by Agriculture and Agri-Food Canada) (AAFC, 2024). Greenhouses[9] account for about 3% of total farms (over 5,200 facilities) (StatCan, 2022).

Total farm cash receipts[10] have grown every year since 2011, achieving a record $100 billion in 2023 (StatCan, 2024b). At the same time, the 2021 Census of Agriculture demonstrated that in 2020, farmers, on average, incurred 83¢ of expenses for every dollar in revenue (AAFC, 2023a). In some cases, farm operators themselves may not be benefiting proportionally from increasing farm revenues, since they are shared with a range of agribusiness corporations, including companies that manufacture and sell, for example, fertilizers, chemicals, machinery, fuels, technology and other materials, or those that provide credit (Qualman & NFU, 2019).

Canada is a world-leading producer of many food commodities but depends on imports for some products

Beyond feeding people in Canada, the agri-food sector across the country plays an important role in food production for global markets, as reflected by its position as one of the largest suppliers (in terms of value) of agricultural products in the world (Statista, 2023a). In 2023, Canada ranked eighth in the world behind the United States, Brazil, the Netherlands, Germany, China, France, and Spain in total exports of agriculture and food products, including seafood and processed foods (AAFC, 2024). The top ten agricultural commodities produced in Canada in 2022 (by tonne) were wheat, rape or colza seed, maize (corn), barley, cow milk, soya beans, potatoes, oats, dry peas, and dry lentils (FAO, 2024a), while top imports included maize (corn), raw cane or beet sugar, and cake of soya beans (FAO, 2024b). In terms of produce, Canada is a net importer; $6.8 billion of fresh and frozen fruit were imported in 2021, compared to $0.9 billion exported, while $3.6 billion of field vegetables were imported and $0.7 billion exported. For both fruits and vegetables, the most common export and import country is the United States (AAFC, 2022a,b).

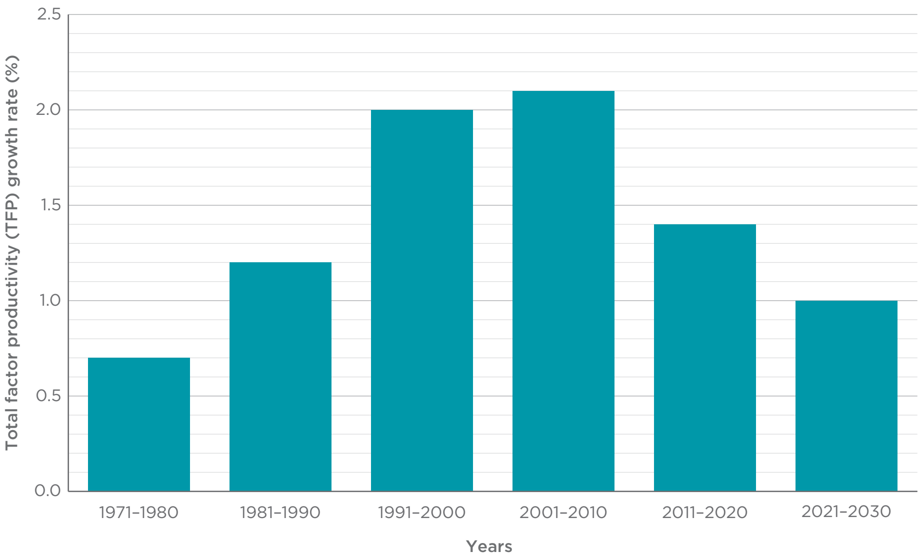
Growth in total factor productivity (TFP) is slowing in Canada

TFP can be defined as "the amount of agricultural output produced from the combined set of land, labor, capital, and material resources employed in farm production" (USDA, 2023a). In short, increasing TFP means more food can be produced with fewer resources (improving environmental sustainability),

9 Including nursery and floriculture production facilities.

10 Farm cash receipts are defined as "the cash income received from the sale of agricultural commodities as well as direct program payments made to support or subsidize the agriculture sector" (StatCan, 2024a).

making it more abundant and cheaper with greater revenues for producers (improving economic sustainability). In these ways, the concept can be linked to food security by supporting a more sustainable food system overall. On a global level, increasing TFP is the primary method to ensure the food supply can meet the growing population's needs with the world's limited resources (USDA, 2023a). While Canada has experienced considerable TFP growth over the past forty years, the growth rate declined over the last decade and is expected to continue to decline (FCC, 2023a) (Figure 1.4). Developments that enabled growth in TFP could also support the economic viability of farm operations, as estimates suggest an increase in TFP leads to a positive change in net cash income. Calculations by Farm Credit Canada (FCC) find that returning TFP growth to its peak levels would result in "as much as $30 billion in net cash income over ten years" as compared to the status quo projections (FCC, 2023a).



Data source: FCC (2023a)

Figure 1.4 Average annual TFP growth in Canada, by decade (1971–2030)

TFP in Canada has continuously risen over the past four decades. The growth rate, however, peaked in the early 2000s before beginning to decline. This decline is projected to continue. Data based on Farm Credit Canada (FCC) calculations using the USDA database on agricultural productivity (available at https://www.ers.usda.gov/data-products/international-agricultural-productivity/).

1.3 Report structure

Building on the context discussed in this chapter, the report examines the promising scientific and technological landscape for atypical production of fruit and vegetables (Chapter 2) and protein (Chapter 3) in Canada. The report then considers the enabling technologies that can help overcome some of the barriers facing these promising production technologies (Chapter 4), including those challenges related to economic viability, as well as the enabling infrastructure required (Chapter 5). The discussion then moves to governance, considering the policies and regulations that can enable success in atypical production (Chapter 6). Finally, the panel reviews the contributions that the adoption, sustained use, and expansion of atypical food production technologies can make to food security in Canada (Chapter 7).

2

Fruit and Vegetable Production

Chapter findings

- CEA offers the ability to grow fruits and vegetables year-round; however, expansion into Indigenous communities—particularly remote and northern ones—requires meaningful upfront consultation and collaboration to ensure the appropriateness and adoptability of technologies.
- Technological advancements in CEA facilities and their various components are targeted at increasing production and improving profitability, energy efficiency, environmental sustainability, food safety, nutritional quality and flavour, and suitability for adverse climates.
- Covering materials, artificial lighting, water and nutrient delivery, climate control, and in situ energy generation are all active areas of technological innovation and improvement for CEA facilities. These technologies additionally benefit from other enabling technologies (e.g., AI, robotics, sensors), resources (e.g., energy, water), and conditions (e.g., access to labour, funding, regulatory approval) to be successful.
- Perceptions of environmental sustainability are drivers of consumer preference for CEA produce; ensuring that environmental goals are met while maintaining profitability is a key challenge for CEA producers.

In Canada, the most relevant atypical food production technology for produce[11] is CEA, which allows for uniform and predictable growth of fruits, vegetables, high-value crops, and mushrooms indoors in locations not necessarily suited for field-based agriculture. CEA can potentially address production deficits for crops that Canada must currently import or cannot grow year-round due to climatic conditions. CEA also provides stability and control over crop production and is perceived to be more resilient to extreme weather events (e.g., droughts, floods, temperature stress, forest fires). In addition, certain aspects of CEA production can use fewer inputs (e.g., water) and less land than traditional field-based produce growing, conserving resources. However, high energy costs for operations can impact the feasibility of some CEA facilities, since ensuring economic viability is necessary in both commercial and non-commercial contexts.

This chapter provides an overview of the current extent of CEA production in Canada and summarizes key technologies associated with CEA, including

11 The terms produce and crops are used interchangeably throughout this report, and refer broadly to fruits, vegetables, and mushrooms.

covering materials, artificial lighting, energy production, climate control, and nutrient and water delivery systems. Technologies are assessed for advantages and disadvantages relating to costs, environmental sustainability, suitability for cold climates, and ease of maintenance and operation. Canada's vast geography and range of environmental conditions mean that no single technological advancement or method is appropriate for all locations. Food producers who use atypical methods will need to consider several factors as they start-up and maintain their CEA facilities, including: the cost of capital expenditures, access to and cost of operational inputs (e.g., energy, water, fertilizers, seeds) and labour, access to markets, the weather and hours of sunlight each month, and the level of critical infrastructure already in place (e.g., clean water, electricity). Implementing CEA facilities in Indigenous communities, especially remote ones, must begin by understanding the needs and capacities of communities to ensure alignment with food security and sovereignty goals before considering the above-mentioned factors.

Canada's vast geography and range of environmental conditions mean that no single technological advancement or method is appropriate for all locations.

2.1 Context

There are a range of technologies that fall under the umbrella of CEA

CEA encompasses a variety of growing systems and facility types, with different technological constraints and advances for optimizing environmental factors for indoor growth. Growers can use many combinations of light sources, climate control systems, covering materials, growing systems, and growing structures[12] (Figure 2.1). CEA can be described as *protected agriculture* or *protected crops*, which includes greenhouses or glasshouses, as well as fully indoor farms, of which vertical farms and container farms are specific types. *Vertical farms* are indoor farms generally described as facilities where plants are arranged on vertically stacked shelves with artificial lights distributed among them (Al-Kodmany, 2018), though alternative structures may also be used (e.g., cultivation towers, rotative wheels, fixed or mobile walls). Kozai and Niu (2020a) use the term *plant factory with artificial light* (PFAL) to describe vertical farming for mass plant production, positioning PFALs as a complementary production method to greenhouses and open-field plant production. *Container*

12 Some of the technologies and techniques discussed in this chapter may also be employed in outdoor agriculture.

farms are plant growth chambers, often in the form of vertical farms, that are housed inside a shipping container and can be deployed in more remote areas (Leroux & Lefsrud, 2021).

The crucial difference between greenhouses and indoor farms is that greenhouses receive natural light from the sun, potentially supplemented with artificial sources, while indoor farms rely solely on artificial light. Depending on the level of technology in a greenhouse as well as external environmental conditions, ventilation, dehumidification, heating, and CO_2 supplementation may be more or less integral to its operations. In contrast, indoor farms are completely enclosed systems and must have adequate dehumidification, cooling, heating, ventilation, and CO_2 enrichment to operate.

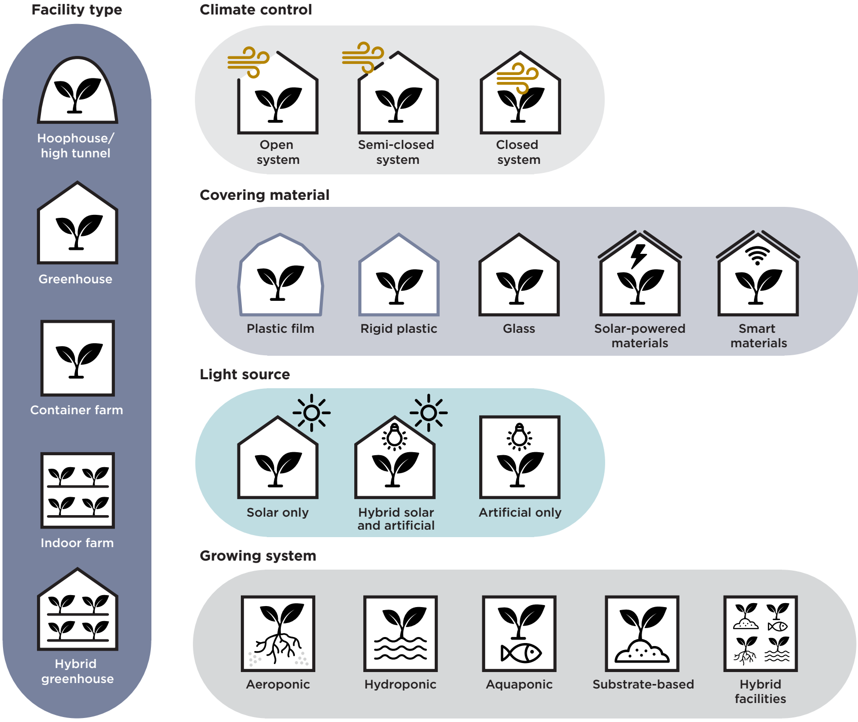


Figure 2.1 CEA facility types and plant growing systems

CEA encompasses several different types of growing systems and facilities. A CEA facility can feature multiple configurations of different lighting sources, covering materials, climate control options, and growing systems. For example, a greenhouse may make use of vertical structures within it to maximize growing space.

CEA is an important part of produce production in Canada

CEA has been practised in Canada for many years, primarily in greenhouses (AAFC, 2023b). In 2022, there were 934 greenhouse vegetable operations[13] in Canada. While greenhouse vegetable farms are concentrated in Ontario (41% of operations) and Quebec (23%), they are also found in the Atlantic provinces (7%), the Prairie provinces (11%), and British Columbia (18%). However, many operations are relatively small in scale, and Ontario accounts for 71% of the total Canadian greenhouse vegetable production in terms of harvested area. Canada is currently a net exporter of fruit and vegetables produced in greenhouses, with an overall trade balance (exports minus imports) of over $1.3 billion in 2022. To meet high demands for produce, greenhouse operators in Canada are investing significantly in technological innovations to improve efficiency, reduce labour requirements, and enhance the quality of produce (AAFC, 2023b).

Fully indoor farms are far less common in Canada; the Greenbelt Foundation reported at least 13 known vertical farms operating in Canada in 2020, located in British Columbia, Alberta, Ontario, and Nova Scotia (JRG Consulting Group, 2020), while a report by CRETAU estimated 17 commercial indoor CEA facilities in operation, including 7 in Quebec (CRETAU, 2020). Container farms have been established mostly as demonstration or pilot projects in smaller communities across Canada. CRETAU (2020) reported that 21 container farms in Canada were operating within urban or peri-urban settings in 2020. According to CRETAU, seven of these container farms were located in Indigenous communities, and the majority were in small towns or villages. A complete listing of facility names or locations does not accompany this analysis, which challenges efforts to update these figures or verify the status of facilities in 2024. In the panel's experience, achieving long-term success with container farms is challenging, and since many of these facilities are experimental or publicly funded, failures are seldom publicized or studied.

In the panel's experience, achieving long-term success with container farms is challenging, and since many of these facilities are experimental or publicly funded, failures are seldom publicized or studied.

Relatedly, listing active indoor farms is futile due to the dynamic nature of the industry in Canada, with frequent expansions and closures challenging efforts to enumerate operational facilities at any given time. Although many of these

13 AAFC (2023b) defines the number of operations as "the number of specialized greenhouse vegetable and fruit operations and includes all other types of enclosed protection used for growing plants, such as rigid insulation, mine shafts, barns and shelters. Mixed operations (vegetables, flowers and plants) are excluded."

facilities have access to initial capital, financial difficulties are common due to high operational costs (Chapter 5) and challenging economic conditions (Aulbur & Schelfi, 2023).

2.1.1 Drivers of innovation in CEA

CEA has been practised in some form for centuries, and technological advances continue to be developed to achieve interconnected environmental, economic, and social goals. Technological advancement targets specific components of facilities (e.g., lighting, covering materials, water and nutrient management, climate control systems) to tackle particular challenges (e.g., cold-weather tolerance, improved circularity, integration with renewable inputs such as energy sources and growing media). It should be noted, however, that a lot of research is primarily driven by economic factors, where improving efficiencies in, for instance, energy use or labour will result in cost savings, with environmental or social benefit as a secondary outcome (Cowan *et al.*, 2022).

It is costly to produce crops in CEA facilities, and their economic sustainability is threatened by uncertainty in marketability and profitability

Fresh food production in CEA is a highly competitive market with relatively low profit margins. To be commercially viable, plants need to be high-value products sold at a premium (Aulbur & Schelfi, 2023). Aspects of CEA products that can be marketed as premium include their freshness, taste, cleanliness, nutritional content, and the fact that they are grown locally and without or with minimal use of pesticides (Kozai & Niu, 2020b; Krasovskaia *et al.*, 2023). Lubna *et al.* (2022) note two broad considerations for CEA businesses: grow-technical challenges and marketability. Grow-technical challenges reflect the ability of an operation to cultivate a saleable product. Once a crop is produced safely at some volume, considerations of marketability—distribution, pricing, and demand, among other factors—come into play (Lubna *et al.*, 2022). Moghimi (2021) estimates the average cost of growing a kilogram of lettuce in the United States using vertical farming is more than double that of field-based farming methods, as higher energy and labour costs exceed savings in water and land use.

Even in situations in which many barriers have been reduced or eliminated, indoor farms may have difficulty maintaining profitability. A study by de Oliveira *et al.* (2022) found that, despite high prices for produce, a rent-free location, cheap labour, and subsidized energy use, a British CEA company's costs could still outweigh revenues in the future, emphasizing continued financial risk. However, access to cheap electricity may lessen these risks;

the operating costs of a vertical farm in Quebec are modelled to be roughly equivalent to operating a greenhouse due to the relatively inexpensive electricity costs paired with reduced land requirements (and therefore lower real estate costs) (Eaves & Eaves, 2018). Many of the countries successfully deploying CEA have significant environmental barriers to conventional agriculture (e.g., limited water and arable land); in these cases, the high upfront and operational costs of CEA can be justified (Gómez *et al.*, 2019). The importance of regional access to resources, including electricity, is further discussed in Section 5.1.1. In the panel's view, technologies to enable economic sustainability are critical areas for targeted research and advancement. Achieving sustainability demands progress in core CEA technologies, as discussed below, but also innovations in other supporting technologies (Chapter 4), in financing R&D and operations (Section 5.2), and in policy-making (Chapter 6).

Purchased energy demand is higher for atypical compared to conventional food production

Energy is a requirement in all but the most low-tech CEA facilities; it is primarily used for climate control (heating, cooling, dehumidification, CO_2 enrichment) and artificial lighting (Hemming *et al.*, 2019). Regardless of the type of facility, energy demands for CEA are much higher than those of conventional field agriculture. For example, the cumulative energy demand for the production and delivery of lettuce to market in New York City and Chicago is 1.3 and 2.0 times higher, respectively, for greenhouse production compared to field production, and 2.3 and 3.1 times higher for plant factory production compared to field (Nicholson *et al.*, 2020). The environmental impact of CEA (relating specifically to power use) depends on the source of energy. CEA facilities that draw from green grids (e.g., powered by hydroelectricity) do not necessarily need to consider the integration of alternative energy generation technologies as compared to CEAs that are off-grid or rely on fossil fuel-based power sources. For example, the CO_2 emissions from vertical farms producing lettuce while using renewable energy sources were found to be around 3.5 times lower than for open-field production due to the use of fertilizers, machinery for harvesting and seeding, and food transportation, storage and waste associated with open-field produce food systems (Vatistas *et al.*, 2022). In this report, renewable and green energy sources are discussed as potential challenges to the implementation of CEA due to the heterogeneity in how power is generated across Canada.

Improving the environmental sustainability of CEA is an ongoing subject of research and technological advancement

One of the greatest advantages of CEA is the much greater crop yield per land area used when compared to field-based agriculture. For example, a literature review by Jin *et al.* (2023) found that, on average, lettuce grown in vertical farms and greenhouses has a light use efficiency that is, respectively, 140% and 70% higher than that of open-field production. This theoretically results in more lettuce production per m^2 through vertical means than by any other method. By growing vertically, producers increase the yield per area and reduce the need for horizontal expansion (as would be required in field-based agriculture). Water requirements are also minimized compared to field agriculture due to the reduced evapotranspiration in enclosed structures, the precise nature of irrigation within CEA, and opportunities for water reuse and recovery (De Pascale *et al.*, 2019; Cowan *et al.*, 2022).

Despite these advantages, CEA still requires substantial environmental inputs—a key goal in recent years has been improving the environmental sustainability of these systems. Desired advances related to environmental inputs include reducing dependence on fossil fuels required to power CEA systems, transitioning processes to be more circular, building with resilient and renewable materials, and requiring fewer resources (e.g., energy, water, nutrients) to produce an equivalent volume of food. Both organic and plastic waste are byproducts of CEA production. Plastic use in greenhouses (including covering material films, floor coverings, propagation trays, clips and truss supports, and tubing) is estimated to result in almost 5,900 tonnes of waste per year, corresponding to 9% of national agricultural plastic waste (Cleanfarms, 2021). Despite producing only a fraction of total agricultural plastic waste by weight, the rate of waste production per hectare by greenhouses is approximately 500 times higher than for non-greenhouse vegetables (Cleanfarms, 2021). This waste may be challenging to recycle due to contamination from soil and plant materials, requiring additional cleaning or sorting steps to effectively reuse (van Os *et al.*, 2022). The valorization of waste products is part of a greater conversation about the circular economy; a fulsome discussion is beyond the scope of this report. However, some discussion of the use of biological CEA waste to feed directly back into CEA systems is discussed in Section 2.2.

Currently, operating costs and associated emissions are a key challenge to the sustainability of CEA systems. Several CEA products have been found to have higher GHG emissions compared to field-based agriculture when considering the entire supply chain, even if field-grown produce is shipped from distant locations (Nicholson *et al.*, 2023; Verteramo Chiu *et al.*, 2024). Improving energy efficiency and shifting to renewable energy sources is critical to the sustainability of CEAs, especially in off-grid and remote areas (Box 2.1) (Cowan *et al.*, 2022). To have the greatest impact on sustainability, CEA systems must be able to connect to readily available sources of green or renewable energies (Cowan *et al.*, 2022). Beyond the GHGs emitted through energy consumption, CEA facilities also emit nitrous oxide (N_2O) from fertilizer application. However, certain forms of CEA may emit less N_2O than field-based agriculture; for example, Karlowsky *et al.* (2021) found that hydroponic systems based on rockwool, which avoid waterlogging the substrate, had N_2O emission factors of 0.1–0.3%, compared to field-based agriculture at ~1%. Beyond emissions from operational sources (e.g., energy, fertilizer), CEA structures are manufactured from building materials (e.g. steel) that have inherent carbon footprints (Cowan *et al.*, 2022).

Box 2.1 Safe, reliable, affordable, and sustainable energy sources

Remote areas of the North are largely dependent on diesel generators for power and fuel oil for heating (Piché *et al.*, 2020); powering CEA facilities in an environmentally sustainable manner is challenging, and several solutions have been proposed. Avard (2015) reviews various potential heat sources for greenhouses in Nunavik. Sunlight is an abundant resource in the summer months and provides more than adequate heat for northern greenhouses; however, sunlight is not a viable heating option for the rest of the year. Solar energy capture and storage technologies would need to advance substantially to provide for year-round production. Extending the growing season into the spring and fall, however, may be possible with solar energy alone using current solar panel and battery technologies, or with relatively low-tech solutions such as heat storage tanks and Trombe walls (walls made of materials that absorb heat during the day and release it at night). Biodigesters and compost may also be used as greenhouse heat sources, though these demand additional built infrastructure (Avard, 2015). Piché *et al.* (2020) observed that the large temperature difference between day and night in the North limits crop growth. To reduce this difference, they deploy a rock and air-based sensible thermal energy storage system. Of course, heat is only one environmental factor; control of lighting, cooling, humidity, and ventilation also require energy in closed systems. For CEA facilities that rely solely on internal light for plant growth, even in the Arctic regions of Canada, heating requirements are minimal as the lights produce enough heat to largely meet demand (Banister *et al.*, 2022). Indeed, more efficient cooling and ventilation systems may be of greater value to CEA facilities than heating alternatives.

CEA can be used to grow produce in regions that cannot support field-based agriculture

Growing crops in protected environments with supplemental lighting and heating allows for extension of the growing season beyond what would naturally be feasible for field growth. An extended growing season may be desirable in places where the climate prevents agricultural expansion, and where the supply of fresh produce is limited or expensive (CCA, 2014; Fressigné *et al.*, n.d.). In certain situations, optimizing CEA technologies for success in cold and remote locations could contribute to food sovereignty efforts in Indigenous communities by offering an alternative to market produce (Wilkinson *et al.*, 2021).

CEA also offers opportunities for agriculture in urban and peri-urban locations where the requisite land for field-based growth is unavailable. In urban contexts, the integration of CEA with existing structures has been suggested as a method to reduce the energy required for temperature control (Martin *et al.*, 2022). Furthermore, certain atypical food production methods such as aquaponics and rooftop gardens are perceived by CEA experts to convey an educational benefit in urban environments through the education of children on food production and the bridging of the producer–consumer gap (Specht *et al.*, 2019).

Improved safety of food is a driver of CEA innovation

Some types of CEA—specifically PFALS—are claimed to be able to produce high-quality, pesticide-free food that requires no washing by the consumer (Kozai & Niu, 2020a). However, these advantages depend on effective pest exclusion and food safety practices. If human or animal pathogens are introduced to a CEA, disease can spread rapidly through recirculated nutrient and water systems (Gómez *et al.*, 2019). Roberts *et al.* (2020) highlight that although many proponents of CEA claim that produce is pest- and disease-free, contamination can nonetheless occur through many avenues. For example, pests may gain entry through ventilation systems, structural defects, inadequate decontamination protocols, and poorly sealed entrances and exits. Small organisms such as fungal spores and spider mites can access even well-maintained and -protected CEA facilities. Vertical farms introduce additional contamination risk, with variations in humidity, temperature, and airflow creating attractive conditions for various organisms both horizontally and vertically within growing structures (Roberts *et al.*, 2020). In the panel's experience, diseases can additionally come from seeds and propagation materials. A CEA facility therefore needs an integrated pest management strategy that includes sanitary practices for workers, sterilization of seeds, water treatment, and air filtration (Lubna *et al.*, 2022). Efforts to provide solutions for pest management are a priority in CEA research; one example from the panel's experience is using microorganisms to protect plants against pathogens.

Implementation of CEA needs to be undertaken with care in Northern and remote Indigenous communities due to their unique cultural contexts

Certain agricultural practices are unfamiliar to some Indigenous Peoples, creating disconnects and reluctance to engage with established methods of food production, let alone atypical ones. For example, interviews conducted by Seguin *et al.* (2021) revealed that many common agricultural terms—including words for fruits and vegetables—do not exist in the Inuttitut[14] language, leading to unclear communication with community members and limited uptake. Ensuring effective communication and relationship-building with Indigenous communities where CEA may be proposed is critical to avoid miscommunication and alienation, and to improve the chances that a project may be adopted and successful (Seguin *et al.*, 2021).

Advancing research into types of crops and food not commonly grown in CEA facilities is a method to incorporate more traditional food sources for communities across Canada. Although leafy greens are the norm in most commercial indoor farms with vertical stacks, in the experience of a member of the expert panel, many other types of crops can be successfully grown in these facilities, including fruits (e.g., strawberries, melons), vegetables (e.g., cucumbers, broccoli), and root crops (e.g. carrots, beets; Figure 2.2). Growing mushrooms indoors through hydroponics has also been successfully implemented in several locations in Canada (see references in Fressigné *et al.*, n.d.) and may be an important contributor to Indigenous food sovereignty when deemed appropriate by the community. The panel emphasizes that although these crops may be more resource-intensive or expensive to grow, the fact that they can be cultivated indoors is important for offering the desired variety to communities wanting to advance food sovereignty.

14 Inuttitut is a regional dialect of Inuktut, the language spoken across the Arctic.

Figure 2.2 Root crops grown in an indoor vertical farm

A carrot (left) and beet (right) grown at the Opaskwayak Cree Nation Smart Farm.

2.2 CEA technologies

The technology used for CEA can be adapted to optimize the key environmental factors relative to the type and development phase of the plant itself. As Kubota (2016) notes, "understanding crop species and cultivar specific growth curves is crucial to obtain maximum productivity in a limited production space." Plant growth and development rates are affected by temperature, CO_2 concentration, humidity, air current speed, nutrients, root zone environment, and characteristics of light—quality (wavelength), intensity, and duration (photoperiod) (Kubota, 2016). Maintenance of optimal production conditions in CEA relies on the integration of monitoring (sensors) and control systems. To be economically viable, a CEA operation must consider yield and energy efficiency; to achieve optimal balance between the two, operators collect and analyze data related to environmental conditions as well as plant growth conditions (Lubna *et al.*, 2022).

The following sections provide an overview of emerging technologies associated with CEA facilities, as well as novel or underutilized methodologies associated with said technologies. Some aspects of CEA facilities, such as internal growing structures (e.g., gutters, carousels, vertical walls), although important, are not discussed because they vary significantly depending on the crop type and discussing them in detail would exceed the scope of this report. The role of digital technologies, including sensors, controls, AI, and robotics related to atypical food production are discussed in greater depth in Chapter 4.

2.2.1 Covering materials

Covering materials have the greatest influence on the microclimate of greenhouses

CEA facilities that depend solely or partially on solar sources of light (i.e., greenhouses) require covering materials that must balance the transmission of light with the loss of heat (dependent on material properties and number of layers) and structural integrity (to withstand the weight of snow or impact of hail), as well as economic trade-offs (the cost of materials). A focus on maximizing energy production while maintaining the environmental sustainability of facilities involves amplifying the use of natural sunlight and using insulation to reduce energy loss through the structure (Hemming *et al.*, 2019). The amount of natural light a facility receives depends on several factors, including its shape and orientation, the amount of direct, diffuse, and ground-reflected radiation, and the transmittance, absorptance, and reflectance of the covering material (Maraveas *et al.*, 2023). By adjusting the amount of solar energy entering greenhouses, producers can increase the efficiency of their systems, reduce the amount of artificial light that they use, and minimize the need for heating during the day (Wei & Chen, 2023).

Producers can augment their facility’s covering materials by adding specific coatings or particles intended either to manipulate the solar spectrum to be more efficient for plant growth or to enhance certain characteristics (e.g., reduction of heat loss and strength) (Maraveas *et al.*, 2023; Mishra *et al.*, 2023). Table 2.1 lists the proposed benefits and drawbacks of materials that are less widely deployed or that are still in testing and development phases, while Table A.1 in the Appendix lists commonly deployed technologies to serve as a comparison.

Table 2.1 Novel technologies for covering materials

Technology	Proposed benefits	Potential limitations	Relevant references*
UV transmitting films	• Improvement in flowering and pollination • Higher quality vegetables • Improved resilience to insect and fungi damage	• Reduced biomass and production • Smaller plants	Meinen *et al.* (2022)
Ethylene tetrafluoroethylene (ETFE)—a type of UV transmitting film	• Longer lifetime than polycarbonate • Dust repellant • High light transmittance • Can be installed in multiple layers for better thermal performance	• High cost • Limited installation expertise in canada	Muñoz-Liesa *et al.* (2022)
Spectral manipulation: 1-dimensional photonic crystals	• Precise spectral blocking • Easily designed and customized	• Customization competes with light transmission	See references in Mishra *et al.* (2023)
Spectral manipulation: plasmonics	• High efficiency for light absorption and conversion to heat	• Costly and difficult to fabricate • Uncertain long-term stability	See references in Mishra *et al.* (2023)
Spectral manipulation: luminescent downconversion	• Tunable and scalable • Improved plant biomass	• Some types may have poor efficiency and long-term stability • Difficulty in emitting blue light • Potentially toxic	See references in Mishra *et al.* (2023)
Spectral manipulation: luminescent upconversion	• Can passively convert low thermal radiation to high photosynthetically active radiation wavelengths	• Poor conversion efficiency in diffuse solar radiation • Substantial additional research required	See references in Mishra *et al.* (2023)

*Panel expertise and experience is an additional data source.

2.2.2 Artificial lighting

Artificial lighting is critical for extending growing hours and may be manipulated to achieve various goals within CEA systems

Vertical and container farms depend on artificial light sources, while some greenhouses also use supplemental lighting to extend their growing hours beyond what is possible with natural light. Light sources for CEA include fluorescent lamps and high-intensity discharge lamps (e.g., high-pressure sodium [HPS] lamps), though LED lamps are increasingly popular given their comparative advantages (Fujiwara, 2020) (Table 2.2).

In addition to artificial lights, shading materials are also a part of general greenhouse lighting control. In the summer months, solar radiation may be too intense for optimal plant growth, so shading strategies may be deployed to reduce light intensity and temperature (Wei & Chen, 2023). Similarly, energy curtains may be deployed overnight to conserve thermal energy (Nauta *et al*., 2023). Light abatement screens may also be used to block light from supplemental lighting after sundown, to reduce light pollution outside the greenhouse and to increase light intensity within the greenhouse by reflecting light back at crops (Hanifin, 2019).

Artificial lights can be operated with variable duration, intensity, spectral quality, and interval to both meet the needs of plant growth and reduce energy requirements (Lopez & Runkle, 2017; Wei & Chen, 2023). When selecting artificial lighting, producers must consider energy efficiency and appropriate wavelengths of light. Lamp choice must balance energy consumption, light yield, and the requirements of the crops in question (i.e., specific light spectra and day light integral) (Wei & Chen, 2023). Table 2.2 presents developing artificial lighting technologies, while Table A.1 in the Appendix lists commonly deployed technologies to serve as a comparison.

Table 2.2 Novel technologies for artificial lighting

Technology	Proposed benefits	Potential limitations	Relevant references*
LEDs	• Long-lived and stable • Lightweight and compact • Precise control over spectrum, fully dimmable • Light modulation during the day • Higher lamp and energy efficiency • Better light use efficiency and higher yield than with HPS/metal halide • Low radiant heat • May increase food quality • Lower water consumption by crops	• Higher initial cost than HPS • May require increased resources for heating • Lack of knowledge/research to fully exploit their full potential	Lopez & Runkle (2017); Fujiwara (2020); Dannehl *et al.* (2021a,b); Katzin *et al.* (2021)
Red/far-red ratio	• Increased fruit yield	• Reduced resistance against some diseases • Species and cultivar dependent	Lopez & Runkle (2017); Ji *et al.* (2019)
End of production light treatment	• Extended shelf life by increasing ascorbic acid and carbohydrate concentrations	• Limited research and testing to date	Min *et al.* (2021)
Full spectral control	• Multiple crops in a single installation, many light mixes • Precision control of crop development	• Currently being offered as software-as-a-service	SollumTechnologies (2023); Heliospectra (n.d.); RED Horticulture (n.d.)
Continuous lighting	• Improving efficiency and reducing costs (by avoiding peak daytime electricity hours) • Lower number of lamps for the same day light integral • Lower electrical power requirement during peak hours • Higher productivity	• Crop dependent; not all species are adapted to continuous light • Light pollution	Hanifin (2019); AAFC (2022c); see references in Lanoue *et al.* (2022)
Light spectrum manipulation	• Bioactive compounds may be affected by light quality, improving flavour and nutritional value	• Response to light spectra is species- and variety-dependent	Dorais (2019)
Dynamic light intensity	• Improved crop growth, light use efficiency, and resource use • Can modulate phenotype and metabolite profile	• Not reported in the literature	Lawson *et al.* (2024)

*Panel expertise and experience is an additional data source

2.2.3 Nutrient and water delivery systems

Growing system and choice of growing media will have a significant impact on the environmental sustainability of the system

Some CEA systems may make use of alternative modes for the delivery of water and nutrients to improve efficiency and reduce inputs, with or without growing media (Box 2.2). Hydroponic systems are "soilless culture[s] with or without growing media where water and nutrients are provided by the irrigation system (e.g. sub-irrigation, drips, sprinklers, mists, deep water systems)" (Dorais, 2019).

Box 2.2 Growing media

There are variable definitions of hydroponic systems; some consider a strict delineation where plants are grown in solution with no other solid media, while others include systems that use physical substrates (Raviv & Lieth, 2008). Growing media provide physical structure for rooting, to maintain water-to-air ratios, and to optimize pH balance for nutrient uptake (Verhagen, 2009). With projected increases in the vertical farming industry worldwide, there will be a commensurate increase in demand for growing media, which are largely derived from organic materials such as peat, coir, bark, compost, and wood fibre, as well as inorganic materials such as perlite and rock wool (Blok *et al.*, 2021). Blok *et al.* (2021) project an increase of 200–1,000% in markets for such materials between 2017 and 2050. This expansion is problematic due to the unsustainable nature of some of these substrates. For instance, peat harvesting is associated with a significant loss of carbon stocks, which cannot be rebuilt in the short or medium term (CCA, 2022). In the panel's view, more research is needed to assess existing growing media in terms of cost, availability, circularity, sustainability, and other variables to determine the best growing medium for achieving various goals.

Technological advances in hydroponic systems include improvements in nutrient management systems, disinfection systems, selective ion removal technologies, and nutrient sensors and controls (Son *et al.*, 2016). Water usage can be low for a closed-loop hydroponic system; however, the availability of sufficiently clean water can be a limiting factor (Niu & Masabni, 2018). Water may also be recycled after use in CEA systems, but residual nutrients and salts make the process challenging (Dorais *et al.*, 2016). Other nutrient delivery systems include spraying bare roots with a nutrient mist *(aeroponics)* and drip irrigation (Van Gerrewey *et al*., 2022). The combination of aquaculture and hydroponics *(aquaponics)* is conceptually promising for its production of both fish and plant crops in a closed system, but the realities of combining these two environments have proven challenging (Lubna *et al*., 2022). However, decoupled plant and fish farming systems may be more complementary; Gravel *et al*. (2015) found that fish effluent used as a soil amendment can improve plant growth and soil suppressiveness in tomato plants, which may then reduce the prevalence of soil-borne diseases. Table 2.3 presents novel technologies for water and nutrient delivery, while Table A.1 in the Appendix lists commonly deployed technologies to serve as a comparison.

Table 2.3 Novel technologies for water and nutrient delivery

Technology	Proposed benefits	Potential limitations	Relevant references*
Potassium hypochlorite for disinfection	• Generated in situ • No phytotoxic effects • Reliable and affordable • Reduced loss	• Not reported in the literature	Bandte *et al.* (2016); Rodriguez *et al.* (2022)
Ion selective electrode	• Sensitive to single ion concentration • Allows for monitoring of nutrients	• Costly • Needs calibration, replacement • Not always accurate	See references in Paul *et al.* (2022)
Ion exchange membranes	• Selectively orient the motion of either anions or cations, which can remove undesirable ions from irrigation water or drained water	• Requires periodic polarity reversal due to charge accumulation	Campione *et al.* (2020)
Non-thermal (cold) plasma	• Effective in disinfecting irrigation water and preventing fungal growth • On-demand source of nitrogen for fertilization • Enhanced biomass production	• Excess can reduce crop yield • Treatments can be unstable in terms of flux and timing • Plant species- and plant organ-dependant	Cannazzaro *et al.* (2021); Rouwenhorst *et al.* (2021); Carmassi *et al.* (2022)

*Panel expertise and experience is an additional data source.

2.2.4 Humidity, temperature, and CO_2 regulation

HVAC systems generally use electricity to run motors for fans and pumps, and fuel (e.g., propane, natural gas) for heating (RII, 2022). Natural gas can also be used for combined heat and power systems in off-grid locations. A more environmentally sustainable option is the electric heat pump when it can be run using on-site renewable energy or grid-provided power (RII, 2022). As such, the novel technologies for improving HVAC overlap significantly with in situ energy production more generally and are therefore also discussed in Section 2.2.5.

Managing humidity within CEA systems is a substantial challenge

The enclosed nature of CEA facilities, combined with plant evapotranspiration processes, creates challenges for maintaining optimal humidity throughout the structure (Gómez *et al.*, 2019). Humidity levels must be balanced against temperature and ventilation costs, and ventilation also increases the risk of CO_2 loss and potential pest introductions (Gómez *et al.*, 2019; Roberts *et al.*, 2020). Controlling humidity can convey a significant expense in some facilities, more costly than heating or lighting (Udovichenko *et al.*, 2021). Humidity and condensation can contribute to fungal growth on plants (Lubna *et al.*, 2022), which can lead to phytosanitary and food safety concerns and can result in crop losses or unsaleable products.

Supplemental heating and cooling require significant energy sources in cold or hot climates

Internal temperatures for greenhouses depend on a combination of thermal energy from the sun and supplemental heating or cooling. Climatic conditions—dependent on geographic location and seasonal weather—will affect the need for supplemental heat and cooling, both diurnally and seasonally. Greenhouses in cold climates demand energy for space heating (overnight and in winter months), which often relies on fossil fuel sources (Wei & Chen, 2023). Even commercial CEA facilities in temperate regions require supplemental heating; southern Ontario greenhouses rely on grid electricity to power lighting and pumps, while using natural gas, biomass, or oil for space heating purposes (IESO, 2019; Naghibi *et al.*, 2021). Producers who use greenhouses can conserve energy and reduce related costs by optimizing the building envelopes of their greenhouses and by using renewable energy (Section 2.2.5). They can also store thermal energy to minimize the energy requirements of supplemental heating and cooling.

CO_2 control in CEA allows for greater yield of produce

In addition to light and nutrients, plants require CO_2 for photosynthesis, the basic process underlying plant growth. Increasing CO_2 can boost yield by increasing photosynthesis or reduce the light requirements while maintaining yield, decreasing energy requirements and potentially enhancing profitability

(Holley *et al*., 2022). Table 2.4 presents technologies associated with CO_2 production, while Table A.1 in the Appendix lists commonly deployed technologies to serve as comparison.

Table 2.4 Novel technologies for CO_2 production

Technology	Proposed benefits	Potential limitations	Relevant references*
Agro-industrial symbiosis system	• Makes use of industrial CO_2 emissions, reducing carbon taxes while increasing agricultural output	• CEA facility needs to be proximal to an industrial CO_2 emitter • CO_2 may require purification and change in concentration	See references in Wang *et al.* (2022)
Carbon capture and utilization; direct air capture	• Carbon neutral in that no additional carbon is created	• A suitable material for agriculture has yet to be identified; requires strong adsorption of ambient CO_2, stable desorption, low consumption of energy, and highly adaptable to dusty and moist conditions	See references in Wang *et al.* (2022)

*Panel expertise and experience is an additional data source.

2.2.5 In situ energy production

As noted in Section 2.1.2, CEA facilities connected to green grids may already be environmentally sustainable or carbon neutral. However, off-grid facilities or facilities that are connected to grids relying on fossil fuels for energy generation may benefit from the integration of in situ renewable energy production. Although emissions upstream and downstream of CEA production are also important to consider when determining the environmental sustainability of facilities (e.g., landfilling of residues), a fulsome discussion of these topics is out of scope for this assessment.

Integration of renewable energy sources into CEA facilities impacts environmental and economic sustainability

Hybrid renewable energy systems in greenhouses and growing facilities provide some improvements to the sustainability of lighting and HVAC systems, thereby reducing GHG emissions (Table 2.5). For example, photovoltaic technologies may be incorporated as components of covering materials to make use of solar energy and produce electricity within the CEA facility (Gorjian *et al*., 2021; Kumar *et al*., 2022). The electricity produced may be fed back into the electricity grid the facility is connected to or stored in batteries on-site to power systems directly (Bartok Jr., 2017). In situ biomass reactors may also use organic waste originating in CEA facilities, such as stems and leaves, to create new products and work toward more circular systems. Waste from vegetables can be fed into bioreactors to create a variety of products including biofuels and fertilizers (Moreno *et al.*, 2021). Biowaste could also be incorporated into growing substrates, which are largely single-use (Salinas-Velandia *et al.*, 2022). However, different residues from even the same plant will have variable compositions (e.g., stems versus leaves), potentially requiring different processing facilities or techniques (Moreno *et al.*, 2021). Biological residues from CEA may also require pretreatment or mixing to achieve desired chemical compositions or densities to be able to be used in anaerobic digestion, composting or combustion processes (Reinoso Moreno *et al.*, 2019; Manríquez-Altamirano *et al.*, 2020; Hashemi *et al.*, 2021), and in the panel's experience, post-treatment to convert N-NH4 into N-NO3 or to eliminate any plant or human pathogens.

Beyond greenhouse waste, anaerobic digestates could also be used to recycle waste from elsewhere in the community to create energy for CEA facilities. For example, one panel member's research is testing the solid and liquid digestates from waste recycling initiatives at the Canadian High Arctic Research Station (CHARS) to act as fertilizer for CEA systems.

There may be unique considerations for implementing in situ energy generation in CEA operations based in cold climates

There is only limited research on the application of in situ energy generation in colder climates (Udovichenko *et al.*, 2021). Syed & Hachem (2019), for example, demonstrate the potential to achieve a net-zero energy design through a combined greenhouse-retail complex with on-site solar photovoltaic arrays modelled in Calgary. Still, outside of urban centres, reductions in GHG emissions through local indoor production have yet to fall below the emissions created by importing food. For example, in a case study of a retrofitted facility in Fort Chipewyan, Alberta, Udovichenko *et al.* (2021) calculated three-fold higher emissions from local hydroponic lettuce production relative to imported lettuce. Despite an on-site solar photovoltaic array, much of this energy disparity was attributable to the community's reliance on diesel combustion for electricity during winter (Udovichenko *et al.*, 2021).

In addition to primary energy sources, CEA systems require backup energy sources to account for unpredictable and extreme weather events, which are becoming increasingly common across Canada; such backup systems prevent total product loss in the event of power outages (Wilkinson *et al.*, 2021).

Critically, cheaper and more energy-efficient implementation of CEA relies on external progress by governments and communities, such as investment in renewable energy grids (Chapter 5).

Table 2.5 reviews select renewable energy technologies that may be integrated in situ with CEA facilities, while Table A.1 in the Appendix lists commonly deployed technologies to serve as a comparison.

Table 2.5 Novel technologies for in situ power generation through renewable sources

Technology	Proposed benefits	Potential limitations	Relevant references*
Organic photovoltaic modules	• Partial transparency and flexibility (less shading) • Lightweight	• Low efficiency • High cost • Reduced durability	See references in Kumar *et al.* (2022)
Dye-sensitized solar cell	• Semi-transparent	• Low efficiency • High cost • Reduced durability	See references in Kumar *et al.* (2022)
Hybrid photovoltaic/ thermal collector	• Creates both electricity and heat • Higher efficiency than photovoltaic	• Can cause shading • Higher cost and maintenance needs	See references in Kumar *et al.* (2022)
Metal plate solar collector	• Low cost • Simple installation	• Poor efficiency • Lifespan less than that of the building	See references in Ding *et al.* (2021)
Glass solar collector	• High efficiency • Low cost	• Lifespan less than that of the building	See references in Ding *et al.* (2021)
Ceramic solar collector	• Long-lived • Low cost	• Less efficient than glass	See references in Ding *et al.* (2021)
Wind turbine	• Established technology for power generation	• Only applicable in locations with adequate wind	Xydis *et al.* (2020)
Anaerobic digestion energy	• Nutrient recovery • Energy production • Circularity	• Digestate management and storage • Difficult to digest greenhouse crop residues (e.g., stems) • Presence of pathogens • Need a pre- or post-treatment	Gontard *et al.* (2018); Belley *et al.* (2023)

*Panel expertise and experience is an additional data source

2.3 Consumer adoption

Consumer perceptions of food grown in CEA vary depending on the type of CEA facility producing it. Several intersecting factors dictate consumers food preferences; however, taste, safety, price, and nutritional value are generally the most notable (Broad *et al*., 2022).

Greenhouse produce is common across Canada and is largely noncontroversial

As discussed, greenhouse production contributes a significant portion of the produce sold to Canadian consumers; at the same time, it has remained largely free of negative perceptions and may be seen as preferred to other methods. For example, a study by Coyle and Ellison (2017) compared consumer perceptions of lettuce grown in vertical farms, mid-tech greenhouses (hydroponic, single layer) and field-based agriculture, and found that greenhouse-grown produce was perceived to be more natural, safer, and higher quality than vertically farmed lettuce. It was also perceived to be safer and of higher quality than field-grown lettuce (Coyle & Ellison, 2017).

High costs drive negative consumer associations with vertical farming, while perceptions of environmental sustainability foster positive ones

A survey of CEA experts concluded that while greenhouse produce is generally well accepted by consumers, some people may be wary of vertical farming due to perceived economic barriers (Specht *et al*., 2019). A negative perception of vertical farming relating to high prices was also observed in international surveys by Jaeger *et al.* (2023) and Ares *et al.* (2021), with the former also reporting on concerns about the perceived loss of rural towns. In the experience of an expert panel member, there may be distrust of food grown hydroponically indoors within Indigenous communities, stemming from the lack of soil and natural sunlight. However, introducing CEA-grown crops through community giveaways and in conjunction with health programming may improve acceptance and promote community involvement in choosing what is grown in the facility.

> "The best way for the CEA industry to make this case is to actually deliver on its promises, providing high-quality produce that competes with existing options on price and … properties such as taste and freshness, as well as demonstrably meet[ing] the triple-bottom-line of sustainability" (Broad *et al.*, 2022).

While a review of research related to consumer acceptability of produce from vertical farms found some negative views, there were also positive opinions. These were linked to claims of increased sustainability, higher production yields, and increased access to food (Son & Hwang, 2023). Additionally, perceptions of the positive attributes of local produce have been observed to drive increased consumer valuation of CEA-grown products (Nishi, 2017; Krasovskaia *et al.*, 2023). The reputation of food production businesses relies as much on demonstrating reduced environmental impacts as on food quality (Light Science Technologies, 2023). As Broad *et al.* (2022) conclude following structured interviews on CEA perceptions by consumers in New York City, "the best way for the CEA industry to make this case is to actually deliver on its promises, providing high-quality produce that competes with existing options on price and … properties such as taste and freshness, as well as demonstrably meet[ing] the triple-bottom-line of sustainability."

Adoptability is limited if there is a mismatch between the produce grown by CEA and the preferences of Indigenous communities in the North

When considering the adoption of CEA facilities in Northern Indigenous communities, ensuring that Indigenous communities want to consume foods that can be successfully grown within facilities is essential. For example, foods commonly selected and grown by non-Indigenous producers—who make choices based on indoor growing practicalities and selected nutritional aspects—are not the same foods preferred by residents of northern communities (Fressigné *et al.*, n.d.). Outdoor growing in northern climates has focussed on root crops which are of high value, especially to Indigenous Elders (Loring & Gerlach, 2010); the lack of diversity of produce currently grown in CEA has been identified as a barrier to the adoptability of CEA in the North (Kozachenko, 2020). Improving the ability to grow a more diverse array of nutrient-dense and staple crops within CEA facilities may improve adoptability (Wilkinson *et al.*, 2021), as could the cultivation of traditionally harvested species (Section 6.3).

2.4 Conclusion

Several types of CEA are operational at both commercial and community scales in Canada, and myriad technological advances comprise these systems and facilities. The aspirations of CEA producers might be fulfilled by improvements to artificial lighting, covering materials, in situ power generation, humidity and temperature controls, and water and nutrient delivery. Some of the goals that may be addressed through technological improvements and innovations in CEA include achieving greater environmental sustainability, improving the nutrition and safety of food, creating systems that are more economically efficient, and diversifying food systems in locations with limited access to fresh fruits and vegetables. These goals link to specific aspects of food security, further expanded upon in Chapter 7.

The panel notes, however, that any application of technology or implementation of CEA facilities is reliant on enabling conditions, such as adequate infrastructure, a trained workforce, supportive government policies, and in the case of facilities intended to provide produce to Indigenous communities, community buy-in and leadership (Chapters 5 and 6). Furthermore, some technologies require support from other technologies and so may be improved by advancements in digital technologies, robotics, and gene editing (Chapter 4).

3

Protein Production

Chapter findings

- Changing consumer preferences and the potential benefits of a diversified food system for improving resilience suggest a need to consider the role of atypical protein in the Canadian food system.
- Canada's existing leadership in protein production creates an opportunity for further innovation in the atypical protein production space, applying a protein portfolio approach.
- The field of cellular agriculture, including cultured meat and precision fermentation, shows promise in terms of diversification of options; however, considerable technical and scale-up challenges remain.
- Many plant-based meat alternatives are on the market, and research efforts in this field focus on improving production processes and consumer appeal.
- Research suggests that convenience and price are the considerations that have the greatest influence on whether consumers want to try novel protein products, while sociocultural and ethical perspectives may also impact uptake.

Protein is an essential part of the human diet, but the nature of its consumption is changing, as concerns related to the long-term sustainability of protein production practices, shifting consumer preferences, health concerns, and other aspects impact what people choose to eat. These changes suggest a need to consider the potential role of atypical production technologies, alongside ongoing efforts to improve conventional protein production, in supporting the diversification of the protein production industry in Canada.

This chapter reviews the motivating factors for atypical protein production in Canada before exploring four production areas purported to address sustainability issues and their associated technological challenges. These areas are plant-based meat alternatives, precision fermentation, cellular agriculture, and alternative protein sources (e.g., seaweed). The chapter then discusses the challenges and opportunities associated with the adoption and acceptance of novel protein types in Canada and globally. However, the lack of commercialization or widespread adoption of some of these technologies makes it difficult to assess the potential benefits to the various aspects of food security; nevertheless, in the panel's view, this emerging sector has the potential to contribute to future food system resilience.

3.1 Context

Canada is a leader in protein production and has an opportunity to expand its strengths

Canada is one of the largest exporters of agricultural commodities, with the protein portfolio playing a key role (Section 1.2.2). The country is particularly renowned for its strengths in plant-based proteins (Invest in Canada, n.d.), and is a leader in the export of protein-rich crops, including wheat, soy, oats, chickpeas, fava beans, dry peas, and canola (Protein Industries Canada, 2021). Canada is also the top producer of lentils in the world (Helgi Library, 2023). In addition, meat is a highly valued agricultural export, with the meat industry contributing significantly to Canada's exports and processing sector; annual meat sales totalled over $35 billion in 2021 (Statista, 2024; CMC, n.d.-a). Thus, Canada is coming from a place of strength with regard to commodity production in protein, and the federal government has recognized the potential for growth (Protein Industries Canada, 2021). For example, the creation of Protein Industries Canada as one of Canada's five global innovation clusters demonstrates government commitment to expanding the value of protein-rich crops to meet increasing global demand for novel foods and plant-based meat alternatives (ISED, 2023).

Several emerging protein areas provide opportunities for diversification

Protein is a critical nutritional component and may be obtained through the consumption of a variety of foods, including dairy, meat, and plants (Russell *et al.*, 2023a). Plant-based proteins have long been a part of the human diet. For example, seitan (a protein product made from wheat) and tofu and tempeh (made from soybean) are plant-based meat alternatives that have been used for centuries in Asian cuisine (He *et al.*, 2020); these products are widely available in Canadian supermarkets. There are also many vegetarian and vegan meal options featuring protein sourced from whole, non-animal ingredients, such as beans, peas, lentils, mushrooms, nuts, and seeds. When discussing plant-based proteins, the panel focusses only on those plant-based products being designed and marketed as *meat alternatives,* aligning with the expansion of research to better mimic the taste and form of meat.

Beyond plant-based meat alternatives, many of the technological advancements related to alternative protein depend on the production techniques of *cellular agriculture*. Cellular agriculture can be defined as "the field of growing agricultural products directly from cell cultures instead of using livestock" (Khan, 2022). There are two main types of cellular agriculture: precision fermentation and tissue engineering. Precision fermentation[15] is also called acellular agriculture and involves using microbes to produce proteins or other organic molecules of interest using fermentation (Stephens *et al.*, 2018). The process of growing meat outside of a whole organism in a laboratory setting is called tissue engineering, which is also known as lab-grown, cultured, clean, cell-based, or in vitro meat (Stephens *et al.*, 2018). The terminology in this sector is evolving. To avoid confusion or contradictory terms—since microbes are cells, calling microbial production "acellular" appears a contradiction—this report uses the term *precision fermentation* to describe the use of microbes to produce food ingredients, and *cultured meat* when discussing alternative methods of protein production based on growing animal cells outside of an animal.

In addition to studies of plant-based meat alternatives, precision fermentation, and cultured meat, active research programs examine the potential for atypical livestock and cropping systems (those that are atypical in the Canadian context) to help meet protein demands. These include advancements in seaweed cultivation and insects as food and feed. Although insects as animal feed are considered out of scope for human food security, in the panel's view, the potential role of insects in terms of environmental sustainability is a valuable inclusion.

3.1.1 Drivers of innovation in atypical protein production

Options for protein sources and consumer preferences are changing

The future demand for protein production in Canada and around the world will likely be influenced by changes in dietary preferences, along with consumer priorities related to affordability, sustainability, cultural significance (Box 3.1), animal welfare, and personal health. Cost, for example, is an important factor in consumer purchasing decisions—in the past, when prices increased, many consumers surveyed (38%) reduced or stopped purchasing beef altogether (Charlebois *et al.*, 2016). The daily intake of protein recommended by Canada's

15 Conventional fermentation is defined as the "cultivation of microorganisms such as bacteria, yeasts and fungi to break down complex molecules into simpler ones" whereas precision fermentation is more targeted, "where all available resources are diverted to produce the desired compounds and little else" (Teng *et al.*, 2021).

Food Guide has also risen in cost; in 2007, the suggested serving size cost for adults (19–50 years of age) was $3.03 for females and $3.76 for males. In 2019, these costs rose to $3.58 and $4.33, respectively (Taylor *et al.* 2023).

Box 3.1 Traditional food consumption among Indigenous communities

Indigenous communities continue to desire traditional foods in their diets, including meat hunted or food harvested from the land (Chan *et al.*, 2019). The First Nations Food, Nutrition and Environment Study included a household questionnaire on diet, health, harvesting, and food security that was sent from 2008 to 2016 to a random sample of First Nations adults living on-reserve across eleven ecozones. Approximately 20% (for men) and 14% (for women) of meat consumed came from wild game, and on days when respondents reported consuming traditional foods, protein intake doubled (from about 75 to 150 grams per day). With the exception of the Mixedwood Plains Ecozone (southwestern Ontario), the majority of traditional foods across all ecozones are animal-based and include a variety of cervids (moose, deer, elk, and caribou), fish (salmon, walleye, and trout), and waterfowl (ducks and geese). Notably, the majority of respondents expressed the desire for more traditional food in their diets (77%) (Chan *et al.*, 2019). Among Inuit communities, traditional foods comprise 23–52% of total protein intake (ITK, 2021). Taken together, these data show that wild harvest (i.e., traditional or country food) provides important protein sources, both nutritionally and culturally. As such, among Indigenous populations, atypical protein production technologies are no more relevant (and may be less relevant) to supporting food security than they are among non-Indigenous populations (with the possible exception of seaweed, which makes up a component of some Indigenous traditional diets; Section 3.2.4). Technological efforts to improve protein production for Indigenous communities may be better focussed elsewhere—such as developing tools to aid traditional hunting and gathering, or mitigating negative impacts of human development on wildlife populations—rather than on atypical protein production technologies. The panel emphasizes that efforts to improve food security in Indigenous communities would be best directed by the leadership and guidance of community members themselves.

Protein Industries Canada (2021) notes that interest in plant-based foods is growing globally, and Canada's plant-based sector is positioned to become a leader. In an online survey of 1,029 randomly selected adults living in Canada for at least a year (response rate 94%), 4% reported eating no meat, 13% reported restricting their meat intake (i.e., occasionally eating meat or fish), and 83% reported having no dietary preferences (Charlebois *et al.*, 2020). Just under a third of respondents stated that they will probably, or fully intend to, reduce their meat consumption in the future; this intention was primarily driven by perceived health benefits and considerations of taste preferences and animal welfare among different demographic groups. There is also a generational shift in meat consumption apparent from the survey results, with the majority of vegans in Canada (63%) under 38 years of age (Charlebois *et al.*, 2020). However, per capita meat consumption[16] in Canada for 2024 is projected to be 88.3 kg, reflecting only a modest decline (–0.7% annualized growth, 2019–2024) (IBISWorld, 2023). Nonetheless, the retail sales value of meat substitutes in Canada rose from $159 million in 2015 to $211 million in 2018 and was projected to increase to $300 million in 2022, though up-to-date information is lacking in the public domain (Statista, 2023b). Alternative protein production technologies are being advanced as a means of addressing the growing global demand for protein, as well as purported growing consumer demand for healthy, sustainably produced, animal-free protein-rich foods (Tian *et al.*, 2016; Clark & Bogdan, 2019a; Siegrist & Hartmann, 2023).

Diversification of protein sources may improve resilience in the face of climate change and disease

> The panel emphasizes that efforts to improve food security in Indigenous communities would be best directed by the leadership and guidance of community members themselves.

Diseases like African swine fever can pose substantial risks to meat industries and the Canadian economy, and must be rapidly eradicated and contained to prevent spread (CMC, n.d.-b). Extreme weather events such as droughts can also significantly affect the supply of certain meats such as beef, affecting availability and prices (FCC, 2024a). Furthermore, demographic modelling reveals that prevailing agricultural and supply chain practices will be insufficient to provide the requisite amount of food for growing global populations (Protein Industries Canada, 2021). COVID-19 revealed that Canada's food supply chain is fragile, depends on external ingredient processing and, despite adequate agricultural commodities, is still reliant on other jurisdictions for many food products (Protein Industries Canada, 2021). Ensuring a diversity of food

16 Defined as "the total carcass weight of red meat and poultry consumed" (IBISWorld, 2023).

sources and producers can help strengthen food system resilience, thereby improving the stability of other aspects of food security (FSC, 2023). Advancing technologies such as cellular agriculture, for example, have been heralded as a way to augment current conventional agriculture, providing an alternative route for producing proteins (Ontario Genomics, 2021).

Perceptions of improved environmental sustainability have been cited as reasons for supporting the atypical protein sector

A phaseout of animal agriculture has been examined as a means of addressing GHG emissions (Eisen & Brown, 2022), and environmental sustainability has frequently been cited as a rationale for pursuing alternative protein sources and protein production technologies (Souza Filho *et al.*, 2019; Humpenöder *et al.*, 2022; van Huis, 2022). However, researchers have yet to demonstrate the specific environmental gains from these technological advances at scale, as well as their ability to replace (rather than supplement) demand for animal meat (Chriki & Hocquette, 2020; Siegrist & Hartmann, 2023).

A review of studies from a range of countries on the replacement of meat with plant-based proteins through vegetarian and vegan diets found a wide range of potential GHG reductions, ranging from 12 to 73% (Kustar & Patino-Echeverri, 2021). Direct comparisons between production methods on an aggregate level should be viewed with caution, however. There is considerable variability in GHG emissions and inputs required for animal agriculture by location in Canada (and around the world) due to differences in production systems (e.g., types of feed, transportation and storage needs, energy costs) (Kustar & Patino-Echeverri, 2021). Additionally, there are environmental benefits of conventional livestock farming (e.g., grazing) (Frank *et al.*, 2002) and research to reduce GHG emissions derived from livestock is active, and progress is being made (Black *et al.*, 2021; Manzanilla-Pech *et al.*, 2021; Acton *et al.*, 2023).

3.2 Atypical protein production technologies

The following sections provide an overview of atypical protein production technologies, focussing on their current commercial availability, technical and scale-up challenges, areas of active research, and opportunities for growth. The panel notes that due to the novelty of some of these technologies, evidence of their viability, sustainability, and acceptability is lacking.

3.2.1 Plant-based meat alternatives

A variety of plant-based meat alternatives are available on the market today, though sales have plateaued

Between 2010 and 2018, annual global sales of plant-based meat alternatives increased steadily (NRC, 2019). However, sales reached a plateau in 2021, with falling stock prices and layoffs for major companies in the plant-based meat alternative space (Osaka, 2023). The market share of these products in 2022 was 2.5% of total retail packaged meat dollar sales or 1.3% of total meat sales (GFI, 2024). That year, plant-based meat dollar and unit sales in the United States declined by 1% and 8%, respectively (GFI, 2024). The slowdown is being linked to products lacking texture and flavour, dissuading consumers from trying or repeatedly purchasing products (GFI, 2024; Askew, 2022). Askew (2022) estimates that improvement of these characteristics—along with nutrient profile and reducing the number of ingredients—will take between 3 and 5 years, limiting further market expansion before then. In the United States, some industry experts suggest that the portion of the population willing to make plant-based meat alternatives a regular part of their diet may have reached saturation (Young *et al.*, 2022). One strategy for retailers is to not over-hype meat alternatives and instead offer them as a complementary item to provide more choices to consumers (Firby, 2022). Key areas of innovation to support further growth and development include increasing and diversifying production, advancing protein extraction, formulation and processing, and increasing opportunities for marketing and distribution (NRC, 2019).

Ongoing research seeks to improve the production, structure, and functionality of plant-based meat alternatives

There are several technological challenges hindering the further development of plant-based alternative meat products (McClements, 2023). One is replicating the look and texture of whole muscle without using animal products. There are a variety of plant-based alternatives to minced meat products—such as burgers, sausages, and nuggets—but few, if any, commercially available products that convincingly replace a whole chicken breast, beef steak, or pork chop. Second is the development of plant-based products with nutritional profiles similar to meat that, to a consumer, also taste, smell, and feel like eating meat. Some products have purported to achieve this, though the sales and popularity of these products suggest further development is needed. Third is cost: even if plant-based products perfectly mimicked their animal analogues, they must also be of comparable (or lower) price than meat in order to influence purchasing decisions for many consumers. Advancements in these three areas will depend on technologies to address machine capabilities and production at scale (McClements, 2023). Indeed, projects supported by Protein Industries Canada are striving to meet these challenges through, for instance, the commercialization of plant-based seafood and improvements in food extraction technology for high-protein foods using Canadian chickpeas (Protein Industries Canada, 2023).

Plant-based meat alternatives also require physical and chemical manipulation to physically mimic the structure and feel of animal tissue. To create these structures, the commercial production of plant-based meats uses extrusion and shear cell processing (McClements, 2023). However, researchers are exploring alternative means of achieving meat-like fibres in plant-based proteins, such as using a combination of a protein derived from corn (zein) in a supporting matrix of starch and pea protein to create textural properties similar to cooked meat (Dobson *et al.*, 2023). This type of advancement could reduce the need for extensive processing in the development of plant-based meat alternatives (Dobson *et al.*, 2023). Other areas of research in plant-based protein seek to improve the environmental sustainability of plant protein extraction (e.g., Hewage *et al.*, 2024) and develop new or improved sources for plant-based meat alternatives, such as peas (Asen *et al.*, 2023; Chigwedere *et al.*, 2023; Yang *et al.*, 2023), lupin seed (Shrestha *et al.*, 2021; Chukwuejim *et al.*, 2023), and other pulses (Nosworthy *et al.*, 2023).

3.2.2 Precision fermentation

Precision fermentation holds promise for effectively mimicking meat and dairy products without the use of animals

Genetically engineering microbes to produce organic molecules of interest is not a new technology and has been used since the 1980s in the cosmetic and pharmaceutical industries (Williams, 2021). For example, the mould *Aspergillus niger,* among other microbes, has been genetically engineered to produce and secrete food-grade enzymes such as chymosin (also known as rennin), an ingredient essential for cheese-making, at industrial scales (Hellmuth, 2006). More recently, the Impossible Burger™ was created using genetically engineered yeast cells to produce a soy-based heme, an iron-containing compound found in hemoglobin, to better replicate a meat-like food experience in a meat-free format (reviewed in Williams, 2021). Mendly-Zambo *et al.* (2021) note three companies that, at the time of their writing, commercially produce fermentation-derived dairy products: Perfect Day, Legendairy Foods (now called Formo), and Real Vegan Cheese (a non-profit research project).

Plant cell and tissue cultures have also been commercialized at an industrial scale in the production of colourants and health food ingredients (Gubser *et al.*, 2021). These methods are used in the production of specific compounds as ingredients (Gubser *et al.*, 2021), rather than as a complete food in and of itself, though research is ongoing in this space (Häkkinen *et al.*, 2020). From the perspective of enhancing food security, precision fermentation could contribute to year-round production of ingredients independent of geographic location and so could provide a homogeneous, controlled food product (Gubser *et al.*, 2021; Wikandari *et al.*, 2021).

Precision fermentation allows for more diverse protein sources, such as mycoprotein

The first mycoprotein, a meat alternative derived from fungi, to be commercially produced was approved for use as food in the United Kingdom in 1983 (Finnigan *et al.*, 2019). The fungus Fusarium venetatum was discovered in the 1960s by researchers seeking a way to convert starch into a protein-rich food (Saeed *et al.*, 2023). To produce the mycoprotein, the fungi are grown under controlled conditions in bioreactors and are then used as a food ingredient in a variety of animal-free meat products (Saeed *et al.*, 2023). Widely available under the label Quorn™ in the United Kingdom and 18 other countries, mycoprotein has been established as a safe and healthy protein source (Souza Filho *et al.*, 2019; Saeed *et al.*, 2023). Research and development is ongoing into other potential sources of mycoprotein beyond *F. venetatum* (e.g., Mandliya *et al.*, 2022). While mycoprotein has yet to become widely available in Canada, this may change. For instance, in January 2023, Health Canada approved Fy Protein™—a protein derived from the fungus *Fusarium* sp. strain flavolapsis by the U.S. company Nature's Fynd—for use as a food ingredient or alternative protein source (HC, 2023a).

3.2.3 Cultured meat

Technological challenges for producing cultured meat include cell sources, culture media, and scaffolding

Cultured meat currently requires beginning with cells from a living animal; technical challenges to producing a standard, predictable product include isolating individual cells consistently and minimizing inter-sample variability (reviewed in Stephens *et al.*, 2018). An alternative to isolating cells from living tissue is the creation of an immortal cell line; however, there are also technical challenges with this concept, including how to genetically engineer or chemically induce infinite replication while also avoiding or removing spontaneous mutations with each replication to maintain consistency of product (Stephens *et al.*, 2018). Moreover, to create variety in commercial production, these technological challenges must be met across a diversity of cell lines or protein types.

Cell culture also requires creating an environment that provides adequate nutrition and other conditions for growth; currently, cells are grown in serum derived from fetal calf, horse, or chicken embryos, to which antibiotics, growth factors, and other hormones are added (Stephens *et al.*, 2018). Optimization of cell culture media, particularly at scale and without the use of animal products, is an active area of research. Efforts to decrease the cost of the growth medium include examining new protocols for functionally active growth factors through recombinant production (Venkatesan *et al.*, 2022) and the exploration of serum-free cell culture media (Skrivergaard *et al.*, 2023). To turn individual cells into meat, they also need to grow on something in sheets or layers. Identifying the materials best suited to this scaffolding is another area of active research (Stephens *et al.*, 2018).

As Rischer *et al.* (2020) note, cultured meat products will also need both to demonstrate adherence to consumer safety regulations and to deliver on taste and texture: "Once all these conditions are met, sustainability is proven, and economic cases drawn up, then the technology could face a real breakthrough." Food safety and consumer acceptance of these products are both unresolved issues that will influence the potential for cultured meat in Canadian markets (Ngapo, 2022).

Scale-up challenges for animal cells differ from those of microbial cultures already in use

While there is no commercial production of cultured meat, proof-of-concept has been demonstrated: in 2013, the first such burger was publicly unveiled (and tasted), but it cost over US$300,000 to produce (Khan, 2022). Humbird (2020, 2021) examined the economics of scale-up for cultured meat using microbial culture as a baseline to understand costs and found, at the time of its publication, it was not yet feasible for producers to reach, at scale, production costs of $25/kg,[17] given several factors. For one, compared to microbes, cellular metabolism is much less efficient, and inhibitor formation is much higher, which limits production at a large scale. Also, the costs of cell culture media and sterilization were too high: cell culture media must either be heat stable (to allow for heat-based sterilization) or filtration[18] costs must be reduced to culture large volumes of animal cells. There would also need to be both improvements in bioreactor design that are specific to cultured meat at industrial scales (e.g., optimizing cell density) and also a means to address the challenge of metabolic waste contamination, particularly in the buildup of ammonia. Humbird (2020) also notes that these are all challenges

17 Defined by the authors as their subjective measure of affordability.

18 Filtration is necessary to remove unwanted bacteria, viruses, and mycoplasma (Humbird, 2020).

related to the production of an animal cell slurry, and do not reflect the additional hurdles involved in turning that slurry into something resembling food (e.g., scaffolding). Recently, progress has been made on reducing cost of cultivated chicken to levels comparable to organic chicken (US$6.2/lb) (Pasitka *et al.*, 2024).

3.2.4 Atypical protein crops and livestock

Cultivation of micro- and macro-algae (seaweed) is an area of opportunity for Canada

Microalgae are single-celled marine or freshwater organisms, whereas macroalgae are multicellular organisms more commonly called *seaweed*. Algae has historically been cultivated and used as food, animal feed, dietary supplements, and in the pharmaceutical and cosmetics industries (e.g., Ferdouse *et al.*, 2018; Leandro *et al.*, 2020; Wang *et al.*, 2021). In Canada, coastal populations of Indigenous Peoples tend and harvest species of seaweed for a variety of purposes, including for food (Turner, 2003; Kobluk *et al.*, 2021). Globally, 30.4 million tonnes of seaweed were produced commercially in 2015, of which 29.4 million tonnes were cultured rather than harvested from the wild (Ferdouse *et al.*, 2018). Seaweed production is dominated globally by Chile, China, and Norway for wild-harvested species, and by China, Indonesia, South Korea, and the Philippines for cultured varieties (Ferdouse *et al.*, 2018). Supplementing animal feed with *Asparagopsis taxiformis* seaweed has been shown to reduce ruminant enteric methane production by 45–68%, presenting a significant opportunity for seaweed to contribute to reducing GHG emissions from conventional agriculture (Roque *et al.*, 2021). Further research is needed, however, to optimize the growth, harvest, and processing of seaweed in a consistent manner, and ensure environmental sustainability and large-scale viability (Lileikis *et al.*, 2023). Beyond acting as a human food source, algae are harvested for use as biostimulants in plant fertilizer (Carvalho & Castro, 2019), and they can also play a role in improving the environmental sustainability of conventional protein production.

While neither a leading producer nor consumer of algae, Canada has a macroalgae industry (Chopin & Ugarte, 2006; Jones, 2023). Small-scale commercial operations are also of increasing interest in certain coastal communities that already practice traditional harvest of seaweed, though more research is needed on the recovery rates following enhanced harvest (Kobluk *et al.*, 2021). There have also been R&D investments in the application of new algal production technologies in Canada (Pankratz *et al.*, 2017).

Microalgae are being explored as a novel protein source for precision fermentation

Compared to other forms of agricultural production, the appeal of microalgae production includes a high nutrient content; low carbon, water, and arable land footprints; the potential to provide additional ecological services (e.g., pollution remediation); and high potential productivity (Wang *et al.*, 2021; Williamson *et al.*, 2024). Microalgae are already produced commercially for human consumption, as well as other purposes, but this production is focussed on only a few species and largely limited to dietary supplements or novelty foods (Villaró *et al.*, 2021). For algae-based functional foods and dietary supplements, particularly in the form of whole biomass or purified protein products, technological developments would be needed to meet the demands of scalable, cost-effective production, and research would also be required to address knowledge gaps related to harvesting and downstream processing (Caporgno & Mathys, 2018; Wang *et al.*, 2021). As with precision fermentation and tissue engineering, microalgae cultures would also need to be able to produce a consistent product that meets food safety regulations (Wang *et al.*, 2021).

Macroalgae, or seaweed, production could be a source of specific nutrients and protein

Seaweed could be considered an alternative source of vegetables, and is already cultivated and consumed as such in some parts of the world (Leandro *et al.*, 2020). As with microalgae, macroalgae are notable for their wide range of constituent components and could be used to address a range of nutritional deficiencies, including minerals, protein, vitamins, and fibre. However, these organisms can also accumulate pollutants, such as heavy metals and metalloids; with production increases, there has been a call for research to investigate appropriate policies and regulations to ensure safety and minimize environmental impacts (Leandro *et al.*, 2020), including those related to habitat availability for native and non-native aquatic organisms (Campbell *et al.*, 2019). Monitoring and research into environmental impacts and mitigation strategies following substantial expansion of macroalgae cultivation can help to maximize benefits (Campbell *et al.*, 2019).

In examining five food and food production models for global food security in 2050, Glaros *et al.* (2022) found macroalgae production may not be appropriate for addressing hunger or undernutrition, but suggests there may be value in pursuing seaweed aquaculture as a source of specific nutrients or ingredients. In the United States, there may be a market for seaweed food products, as 35% of consumers in a willingness-to-pay study elected to purchase at least one seaweed product (Li *et al.*, 2021). Domestication of certain varieties of algae and the selection of desirable traits is an ongoing process, requiring additional research (Diaz *et al.*, 2023).

Though subject to scaling limitations, insect production as animal feed is a promising area for improving sustainability

The consumption of insects as food has been a widespread practice in tropical regions worldwide, and is a recognizable part of the diet of many people in Asia, Africa, and Latin America (Melgar-Lalanne *et al.*, 2019). However, insect production and consumption outside of these regions is limited and is often met with aversion, though attitudes may be beginning to shift (Melgar-Lalanne *et al.*, 2019). Other markets for insect products in Canada include soil additives (specialty fertilizers) and animal feed (notably for poultry, hogs, and aquaculture feed, as well as pet food and treats) (NPC, 2022). In the panel's view, focussing on insect production for animal feed and improving sustainability through reducing food waste has a greater potential impact than insects as a source of protein in food.

The Canadian Food Inspection Agency has approved black soldier fly (BSF) larvae as animal feed in Canada (CFIA, 2022), and its frass (excrement and exoskeletons) has been advanced for use as a soil amendment and pest-control agent (CPD, 2016). Since feed is 50–70% of the expense of aquaculture (Rana *et al.*, 2009), and because relatively inexpensive BSF can be consumed by farmed fish, insects have a potentially significant role to play in the sustainability of this sector (NPC, 2022). In a life cycle assessment of BSF production to a puree and protein meal format, Smetana *et al.* (2019) found that the environmental impacts of insect protein were lower than fishmeal for most categories because of improvements in efficiency, the use of both renewable energy in production and also sustainable feed sources (e.g., biocycling the organic waste products of milling, brewing, or greenhouse production). Compared to plant-based proteins, the impacts of insect protein are only environmentally competitive if produced using renewable energy and sustainable feed; however, they do compare favourably against plant-based proteins when considering specific concerns of freshwater depletion and land use (Smetana *et al.*, 2019). Scale is a significant barrier to widespread market penetration—particularly for livestock, aquaculture, and pet food (NPC, 2022; Larouche *et al.*, 2023).

3.3 Consumer adoption

The protein production technologies reviewed in this chapter point to promising avenues of R&D to diversify Canada's protein portfolio and potentially improve the sector's sustainability. There are also opportunities to improve the nutrition and quality of existing alternative protein products, particularly through advancements in precision fermentation. In some cases, such as for food ingredients, advancements may be largely imperceptible to consumers except, perhaps, as cost savings, improvements in nutritional content, or changes in flavour or texture. In other cases, alternative protein products represent a substantial shift from existing food norms, and significant uncertainty about consumer adoption remains. This uncertainty extends to religious or cultural acceptance of alternative proteins; there is ongoing debate about whether cultured meat could be considered kosher or halal, which would affect the adoption of products by relevant religious communities (Chriki & Hocquette, 2020).

While there has been considerable marketing hype around some aspects of atypical protein production, the uptake of any novel food resource will be driven by consumer preference. For example, over the past decade, plant-based dairy alternatives have been increasing steadily in sales and revenue in Canada (Statista, 2023c). In the United States, plant-based dairy alternatives (marketed as milk) accounted for nearly 15% of all dollar milk sales in 2023; however, it is worth noting that the number of units sold declined by 8% from 2022 to 2023 (GFI, 2023). Preferences for dairy alternatives are associated with age and food values, and many people in Canada purchase both dairy and plant-based dairy alternatives for different purposes (Slade & Markevych, 2024). Given technological advancements and a growing variety of high-quality plant-based alternatives, the industry is expected to grow by around 10% annually from US$1.04 billion in 2024 to US$1.77 billion by 2029 (Mordor Intelligence, 2024).

Unfamiliarity and finding products off-putting may hinder the adoption of protein alternatives

Familiarity with food is an important factor in the acceptance of novel products. For instance, a survey of Canadians found that alternative protein sources that mimic traditional protein sources have higher acceptance rates than those that are unfamiliar to consumers (Music *et al.*, 2021). Age is a significant factor, with younger participants more willing to try novel protein sources. Female survey respondents tended to favour sustainable agriculture as a choice, but were also less likely to adopt novel proteins to support that choice (Music *et al.*, 2021).

Food norms are internalized, and the more novel food products violate these norms, the more disgusted consumers are, thereby limiting their willingness to try them. Koch *et al.* (2021) argue that while consumers may report that they reject edible insects on the grounds that they may carry diseases or that lab-grown meat is unhealthy, these concerns are, in fact, rooted in feelings of disgust. While the most cited reasons to try lab-grown meat and insects were environmental or sustainability considerations, the most significant barrier was customers finding these products off-putting (Jarchlo & King, 2022).

Consumers report various reasons to try (or not) novel protein products, but convenience and price largely influence purchasing decisions

In a review of consumer acceptance of cultured meat, Post *et al*. (2020) found that long-form surveys that provided positive information resulted in more optimistic results (e.g., greater willingness to try these products). In contrast, surveys that offered little information on cultured meat alongside other topics generally resulted in more negative responses. However, detailed descriptions also create more negative perceptions of cultured meat by evoking perceptions of unnaturalness (Post *et al*., 2020). Moreover, until such products are made commercially available, questions remain as to the relationship between a survey respondent's stated preference and the revealed preferences of consumers making purchasing decisions.

For products currently available on the market in Canada, such as plant-based proteins, consumers report considerations of environmental sustainability, health impacts, and animal welfare as reasons for trying these products, yet actual purchasing is more often a result of price and convenience (Clark & Bogdan, 2019a, 2019b; Kevany *et al*., 2022). This is true for seaweed products as well; price was the key determinant in whether consumers were willing to purchase novel products, with the greatest interest in snacks containing seaweed compared to seaweed salads or noodles (Li *et al*., 2021). Consumers were more likely to have purchased less processed protein alternatives, such as canned or dried beans, tofu, and pasta fortified with vegetable proteins, over meat-like plant products (e.g., burgers, nuggets, sausages) (Clark & Bogdan, 2019a). Improving visibility by increasing shelf space and promotional signage for meat alternatives, as well as placing alternatives beside meat products in grocery stores, could help increase consumer purchases (Gravely & Fraser, 2018).

> The panel emphasizes that, as agriculture is a substantial and invaluable component of Canada's economic prosperity, a portfolio approach that includes advancements in both typical and atypical protein production can contribute to the nation's ongoing leadership and resilience in this sector.

3.4 Conclusion

A variety of atypical protein production technologies and areas of scientific advancement could impact the protein sector in Canada. These advancements include improvements to existing, small-scale markets and operations (seaweed), food ingredients and processing (plant-based meat alternatives, precision fermentation), and entirely new methods of producing animal-based protein (cultured meat). However, given the current high levels of protein production and consumption across the country, as well as consumer preferences for familiar products, the impact of these production methods shows little promise in directly addressing food security issues in Canada. Instead, the contributions that atypical protein production technologies could make toward food security would be indirect, through improvements to sustainability and the diversification of the industry to improve resilience.

The panel notes that—while potentially valuable for the long-term success and resilience of Canadian agriculture—the benefits of investments in atypical protein production will be geographically limited in scope and unlikely to directly impact the most food-insecure populations in Canada. For example, to ensure profitability, economies of scale in precision fermentation and cultured meat will demand large industrial facilities for these products. Atypical protein production at a local scale will not be achieved by these technologies. Other types of facilities may work well for smaller communities (e.g., seaweed), but, as with CEA, these will depend on enabling conditions (reviewed in Chapter 5). Still, the panel emphasizes that, as agriculture is a substantial and invaluable component of Canada's economic prosperity, a portfolio approach that includes advancements in both typical and atypical protein production can contribute to the nation's ongoing leadership and resilience in this sector.

4

Enabling Technologies

Chapter findings

- Many varietals being used in CEA operations were optimized for field growth, which prioritizes factors less relevant for indoor growing.
- Gene editing can tailor variants and optimize plant performance for growing conditions in CEA operations, improving productivity and expanding the types of foods that can be produced indoors.
- Robotics and automation can improve productivity and lower labour costs but may not be accessible or appropriate for smaller operations.
- AI supports an increasing number of activities across atypical production, from hardware control in CEA facilities or bioreactors, to simulations for operations or training.
- Many atypical protein production methods are rooted in biomanufacturing and biotechnology, and therefore benefit directly from progress and breakthroughs in AI and genomics.

Advances in CEA, and the growing number of alternative means for protein production, present opportunities to diversify Canada's food system if they are to produce food sustainably. Earlier chapters have highlighted progress resulting from ongoing technical advances within specific fields, such as vertical farming and cellular agriculture. However, realizing the full potential of atypical food production also hinges on advances and adoption of technologies in other distinct fields.

This chapter focusses on the two overarching categories of genomics and digitalization (which includes automation, robotics, and AI), given that they demonstrate the greatest potential to contribute to the environmental performance, economic success, and social relevance of atypical food technologies. These vast fields offer cross-cutting impacts, many of which apply to, and are currently deployed in, conventional food production. Indeed, some of the technologies detailed in this chapter are not novel in relation to food systems but their adoption remains only nascent in atypical contexts. Increased adoption has the potential to address some atypical food system challenges—namely bolstering production and efficiencies to a degree that strengthens business cases and economic feasibility. The panel considers examples across the value chain to demonstrate the numerous potential multiplier effects that may result from integrating enabling technologies into atypical food production.

4.1 Genomic technologies

The purposeful selection of plants with desirable characteristics has been occurring for thousands of years, with the use of phenotypic selection for adaptability to specific environmental conditions. More recently, researchers have sought to optimize crops for agricultural uses, including CEA, through techniques such as cross-breeding, genomic selection, genetic manipulation, genetic editing, and the use of molecular markers (Henry, 2020). Furthermore, techniques and processes found in the growing field of synthetic biology have applied principles of engineering to biological systems, including those involved in producing food (Hamelin *et al.*, 2020). The genomic technologies underpinning synthetic biology draw on numerous tools and concepts from molecular biology. They allow innovators to characterize and manipulate the genomes of biological systems in order to provide new avenues for characterizing food products, alter or create products, and leverage biological processes for manufacturing or processing applications (Cook & Nightingale, 2018; Hamelin *et al.*, 2020).

CEA operators are currently limited to varietals optimized for outdoor growth

A majority of crops used in CEA were initially bred for high yield in fields or greenhouse conditions, or to emphasize shelf life (Fernie & Yan, 2020). Plant characteristics were selected for stable production in the face of pests, diseases, and variable environmental conditions, including changes in temperature and precipitation (Mickelbart *et al.*, 2015; Folta, 2019; Estes, 2022). As discussed in Chapter 2, pests and diseases also persist in controlled environments and present unique challenges not necessarily analogous to those in outdoor farming (Roberts *et al.*, 2020). Similarly, crops have been bred to be more resistant to bruising during transport or selected for their ability to survive shipping (Folta, 2019). When supply chains are shortened, and the need for transport reduced, such traits can potentially be revised to instead re-prioritize flavour, texture, and nutrition (Folta, 2019). Moreover, when plants are grown under controlled conditions, a reduced need for stress and disease tolerance provides opportunities to improve nutritional quality, taste, and growth (Table 4.1).

Table 4.1 Priorities and opportunities for CEA plant breeding

Priorities	Opportunities
• Faster growth • Reduced plant stature • Higher light use efficiency • Easier harvest • Higher crop value • Reduced start-up costs • Reduced energy use	• Novel flavours and colours • Flower induction or suppression • Nutrient manipulation • No pollinators required • Reduced disease pressure • Multiple phenotypes from one genotype

Data sources: Folta (2019); panel expertise

Gene editing provides a new platform for selecting valuable traits in plants, with the potential for faster and more predictable performance

To breed new crop types, CEA operators need to invest in high-cost screening genotypes (knowledge of optimal parents for crossing, or desired characteristics in offspring), which in turn depend on sufficient time, space, expertise and other inputs (Folta, 2019). Gene-editing tools, on the other hand, can make targeted edits to a specific trait (Folta, 2019); however, knowledge of the entire genome sequence is required to create these targeted changes and to avoid impacts on other locations with similar sequences (Henry, 2020). Moreover, genes of interest require identification, as does the technical process of accessing specific genes within particular plant cells (Van Eck, 2020).

Interest in genome editing for crops arose partially as a response to the negative reactions to genetic modification[19] involving transgenes (i.e., foreign genes introduced to a crop) (Kumar *et al*., 2020). Gene editing, including that done through CRISPR/Cas, is different in that it does not include the introduction of a foreign gene but instead functions by editing the existing genome (e.g., through new mutations, replacing a faulty gene). Changes introduced through genome editing are largely indistinguishable from alterations produced through traditional plant breeding techniques, or naturally occurring and chemical mutations (Kumar *et al*., 2020). Furthermore, gene editing is relatively inexpensive and easy to implement, allowing use by smaller labs and companies, thereby promoting market diversity and competition (Qaim, 2020). Gene-edited lines with desirable traits are also easily incorporated into traditional breeding programs (Kwon *et al*., 2020), and most commercial crops have had their genomes altered (Barrangou, 2022). CRISPR/Cas is a widely used method for gene-editing plants and has been

19 The panel uses the term genetic modification to refer to changes to a genome achieved using technology. This process is also known as genetic engineering or genetic manipulation.

influential on crop-breeding methods (Van Eck, 2020; see references in Kwon, 2023). Collaborations between industry and public institutions are underway to explore possibilities to increase crop yield, strengthen plant architecture, and improve plants' consumable characteristics (e.g., colour, taste, texture) through indoor-focussed seed-breeding research (Estes, 2022). Gene edited products will face the same scrutiny as transgenic crops in some export markets despite technical differences from transgenic modification (Macnaghten & Habets, 2020).

Access to a wide variety of traits may enable the production of varieties with properties tailored to specific CEA operations

Instead of genetically selecting plants for optimal field growth, plants tailored for growth in controlled indoor environments can be bred to emphasize alternative traits (Folta, 2019; Estes, 2022). Specialized crop types can increase the likelihood of successful growth and harvest in a CEA facility, reducing the chances of failure and, in turn, improving profitability. Furthermore, most of the crops currently grown in CEAs are leafy vegetables, such as lettuce, which already lend themselves well to this type of growth environment since, for example, most of the plant is edible and grows quickly even under modest illumination (Hiwasa-Tanase & Ezura, 2016). Genetic alteration has the potential to greatly expand the diversity of foods currently able to be successfully grown in CEA facilities.

> Genetic alteration has the potential to greatly expand the diversity of foods currently able to be successfully grown in CEA facilities.

In general, genetic alteration of plants is pursued to either reduce costs associated with production or to make crops more valuable at retail (Folta, 2019) (select adaptations to growth are highlighted in Table 4.2). Alternative traits tailored for cultivation in CEA include quicker growth, smaller size, alternative modes of pollination, adaptation to grow in low light or high relative humidity and temperature conditions, and efficient architecture (for ease of harvest) (Folta, 2019; Estes, 2022; Dorais, 2023). Other examples are adaptation for growth in hydroponics and resistance to specific diseases (Meng *et al.*, 1998 as cited in Henry, 2020), and changes in nutritional value (Box 4.1). Efforts to expand plant diversity in CEA may also apply to the domestication of plants that have cultural significance, or food that is traditionally collected via wild harvest (e.g., berries) by Indigenous communities (allowing for longer growing seasons) (Dorais, 2023). Such efforts may support Indigenous food sovereignty if this domestication is driven by community preferences and needs.

Table 4.2 Examples of CEA-optimized traits accessible through genomics*

Rapid growth	• Speed breeding to shorten generation times (SharathKumar *et al.*, 2020) • Rapid and/or earlier flowering to facilitate continuous production for increased yield (Touliatos *et al.*, 2016; Kwon *et al.*, 2020; Wong *et al.*, 2020; van Delden *et al.*, 2021) • Optimizing light response for increased seedling growth, plant defence production, and metabolic functions (OuYang *et al.*, 2015; Marondedze *et al.*, 2018)
Reduced plant stature	• Breeding dwarf phenotypes permits a greater number of plants to be grown in a limited space (Folta, 2019; Kwon *et al.*, 2020)
Ease of harvest	• Breeding for plant uniformity • Limiting the expression of leaves near fruits and flowers to make robotic harvesting more effective (Folta, 2019)
Reduced energy use	• Adapting plants to optimal light conditions within CEAs, and more specifically, low light conditions (Folta, 2019) • Breeding plants to respond variably to specific light conditions (Folta, 2019) • Adapting plants to take advantage of high CO_2 concentration
Novel crops	• Propagating berries continuously throughout the year (Aung *et al.*, 2014; Kozai & Niu, 2016) • Breeding culturally valued plants that may be negatively effected by climate change in the wild (CANNOR, 2021)
Nutrition and taste	• Fortifying existing crop types to be more nutritionally dense, or targeting specific nutrients that may be lacking in specific markets (Hiwasa-Tanase & Ezura, 2016)
No pollinators	• Reducing the need for mechanical pollination (Folta, 2019)

*Panel expertise and experience are additionally considered as a data source.

Though only in emerging stages, gene-editing research is ongoing to "hack" or "re-wire" photosynthesis, to demonstrate how plants might be manipulated to generate energy or to become increasingly resilient to adverse weather conditions (Kleiner, 2022). Gene-editing research efforts involve transferring certain traits into plants such as wheat, rice,[20] and soybeans that changes how they process and store CO_2 to enable greater heat and drought resistance while potentially increasing yield capacity (Wang *et al.*, 2022; Billakurthi & Hibberd, 2023).

20 Work on "C4 rice," however, has been underway since the early 2000s, and the timeline on commercial applications remains indeterminate (CBC Radio, 2019; Kleiner, 2022).

Box 4.1 Gene editing to enhance nutrition

Alterations of plant components can involve both enhancing and suppressing dietary traits; macronutrients (lipids, fibre, proteins, and carbohydrates) and micronutrients (minerals, vitamins, and functional metabolites) can be emphasized and selected for, while antinutrients (substances that prevent uptake of nutrients) and allergens can be suppressed (Newell-McGloughlin, 2008). To date, many micro- and macronutrients have been genetically enhanced in several crop types, including staples such as maize, wheat, rice, potato, and canola, as well as other produce such as strawberries, apples, tomatoes, and lettuce. There is abundant evidence that certain vitamins and minerals are critical for human health, yet their uptake is limited in certain diets (Newell-McGloughlin, 2008). For example, certain amino acids such as lysine, tryptophan, and methionine cannot be synthesized by humans, but are not abundant in commonly consumed foods like cereals or legumes (Kumar *et al*., 2020). Despite promising research to enhance the nutritional content of CEA plants, there is a lack of evidence supporting significant nutritional improvement of individuals consuming said produce, even in populations with nutritional deficits.

The development of biotechnology-derived genetic traits, including those achieved through gene editing, is not a quick or easy process and requires substantial investments of both time and money. A survey of four multinational seed companies found that the process associated with commercializing a plant with a biotechnology-derived genetic trait (including discovery, development, and regulatory authorization) from 2017 to 2022 cost $US115 million and took an average of 16.5 years (AgbioInvestor, 2022).

Genomics is integral to atypical protein production due to the intrinsic role of biotechnology in production and processing

The ability to manipulate and characterize organisms at the genetic level carries several implications for atypical protein production. In aquaculture, for example, genetic technologies are being applied to enhance valuable traits of certain species, such as growth rate or resistance to disease (Houston *et al*., 2020). For other sources of protein production, meanwhile, the development and improvement of genomics tools are instrumental. The paradigm of cellular

> The paradigm of cellular agriculture, for example, hinges on continued progress in engineering biology (Ontario Genomics, 2021).

agriculture, for example, hinges on continued progress in engineering biology (Ontario Genomics, 2021). Plant-based protein production will potentially benefit from the increasing control over plant genetics to improve nutritional qualities in end products (Le *et al*., 2016).

Characterization tools based on genomics also offer a potential role in facilitating the processing of food products, with potential implications for shelf life and food safety (Cook & Nightingale, 2018) (Section 6.2). Sampling techniques based on genomics and other -omics (e.g., proteomics, metabolomics) can contribute to the accurate detection of pathogens to prevent outbreaks of foodborne illness while also contributing to a better understanding of the associated microbes, such as their provenance and susceptibility to control through antimicrobials (Cook & Nightingale, 2018).

The panel notes that there are also important developments related to genomics and aquaculture, but these largely lay outside the scope of atypical production (examples in Box 4.2).

Box 4.2 Domestication applications for aquaculture

To meet global protein demands in the coming decades, researchers have examined the application of biotechnology, particularly genomics, to aquaculture (e.g., Boyd *et al*., 2020; Houston *et al*., 2020). Notably, the domestication of species for aquaculture is in an earlier stage of development compared to terrestrial species, such as pigs, chickens, and cattle, which have been farmed for millennia (Houston *et al*., 2020). Genome editing could be used to accelerate the domestication and genetic improvement of aquatic species for farming, and to increase the genetic diversity of farmed species (Boyd *et al*., 2020; Houston *et al*., 2020; Hallerman *et al*., 2023). While increasing freshwater aquaculture would also increase demand for freshwater and land resources, Boyd *et al*. (2020) reflect on the attractiveness of expanding coastal and offshore production given the availability of marine resources for aquaculture. Considerations for any such expansion include R&D of technologies to ensure the environmental sustainability of such practices, as well as adaptability and resilience in the face of climate change (Boyd *et al*., 2020).

Microbiome engineering may be a promising approach to improving crop performance in CEA

Microbiome engineering is the intentional manipulation of a plant's microbiome—the collection of microorganisms, such as fungi and bacteria, that live in and around plants in symbiotic relationships (sometimes called symbionts) (Liu *et al.*, 2020; Berg *et al.*, 2023). Manipulation of a plant's microbiome can be beneficial, supporting plant growth and development, providing resistance to stresses, pathogens, and pests, and improving nutrient uptake and accumulation of metabolites, thereby improving productivity and crop yields (Yang *et al.*, 2013; Arif *et al.*, 2020; Edmonds *et al.*, 2020; Berg *et al.*, 2023; Batool *et al.*, 2024). Additionally, a plant's microbiome may also affect the nutritional quality of food that it produces (Kowalska *et al.*, 2015; Escobar Rodríguez *et al.*, 2021), and may offer advantages over approaches that rely on chemical fertilizers (Arif *et al.*, 2020; Thomas *et al.*, 2023). Microbiomes may also be useful for crop monitoring. Stress or disease can affect a plant's microbiome, and these changes may be detectable before symptoms are visible on the plant, thereby providing an early warning system (Thomas *et al.*, 2023). Targeted deployment of bacteria and fungi may also help to reduce food loss from pathogens in post-harvest food storage, and the composition of a plant's microbiome may be used as an indicator of the storability of its harvested produce (Kusstatscher *et al.*, 2019).

Traditional approaches to microbiome engineering include soil amendments of organic and inorganic materials, while more direct approaches to microbiome engineering include the breeding and transplantation of beneficial microbiomes, as well as the development of artificial microbial consortia—sometimes referred to as synthetic communities or SynComs (Jansson *et al.*, 2023; Thomas *et al.*, 2023)—using techniques from synthetic biology (Foo *et al.*, 2017; Arif *et al.*, 2020; Liu *et al.*, 2020). Many approaches to microbiome engineering specifically target the root microbiome as it is a primary determinant of plant development and growth, as well as biotic and abiotic stress tolerance and nutrient uptake (Dubey *et al.*, 2019; Arif *et al.*, 2020). Although the more controlled conditions of CEA (and hydroponic growth in general) reduce the importance of the root microbiome to plant health, the high level of control over the root microbiome has been demonstrated to be beneficial to plant growth (Tan *et al.*, 2021; Thomas *et al.*, 2023). As such, the manipulation of the root microbiome in hydroponic systems through the introduction of consortia of plant-growth-promoting microbes has become a popular strategy (Edmonds *et al.*, 2020).

However, more research is needed to better understand the composition and behaviour of the root microbiome in hydroponic systems, and its relationship to plant performance (Edmonds *et al*., 2020; Thomas *et al*., 2023). Indeed, microbiome engineering in general faces some significant challenges and knowledge gaps (Arif *et al*., 2020), and the understanding of microbiome engineering in hydroponic systems is rudimentary (Thomas *et al*., 2023). Furthermore, the beneficial effects of microbiome engineering produced in the laboratory can be difficult to reproduce in the field or CEA (Vallance *et al*., 2009; Vejan *et al*., 2016; Rilling *et al*., 2019; Jansson *et al*., 2023), and research on the effectiveness of microbiome engineering in hydroponic systems has found mixed results (see references in Thomas *et al*., 2023).

The social perceptions of genomic technologies are heterogeneous and may be influenced by previous introductions of biotechnology into the food system

People in Canada typically have limited knowledge of genomics, genetic modification and gene editing (Busch *et al*., 2022; Vasquez *et al*., 2022), as well as the use of agricultural biotechnology (Yang & Hobbs, 2020; Vasquez *et al*., 2022). The novel or increased use of genetic tools in agriculture biotechnology may be viewed through the antecedent and often negatively tinged lens of GMOs (Macnaghten & Habets, 2020; Shah *et al*., 2021). Survey research on the Canadian public has shown that many attribute negative associations to the concept of genetic modification, and are reluctant to eat foods genetically modified with CRISPR/Cas9 (The Strategic Counsel, 2016; Shew *et al*., 2018).

There is immense geographic and cultural diversity among people in Canada, including Indigenous Peoples. In turn, there is no singular perspective on gene editing or genetic modification in agriculture. Different communities may assess the value of gene editing differently than government regulators or industry (see Hudson *et al*., 2019 for an international example). For instance, issues around open data and genomics in Indigenous communities are linked to agency, sovereignty over lands, and cultural security (Mc Cartney *et al*., 2022; CCA, 2023).

The refusal, reluctance, willingness, or eagerness to support the use of gene editing tools or to consume genetically altered products, is varied and context dependent (Muringai *et al*., 2020; Yang & Hobbs, 2020; Busch *et al*., 2022; Vasquez *et al*., 2022). As with all technologies, levels of adoption and approval can be determined by the degree to which a technology's value and projected benefits align with those held by individuals and communities (Hudson *et al*., 2019; Nawaz & Satterfield, 2022). Also of significance are aspects of transparency, trust, and opportunities for participation in the deployment processes of the technology (Macnaghten & Habets, 2020; Goldsmith *et al*., 2022). At a consumer level, people are concerned not only with the products themselves but also with who profits from them. In a review of relevant literature, Woźniak-Gientka *et al.* (2022) determined that consumers in the United States and Canada believe that the majority of the benefits that stem from novel breeding techniques go to the private sector, with the least benefit going to consumers and universities. Survey results found that Canadian consumers stated they were unwilling to pay for genetically modified foods if they cost more than other products, even when a higher nutritional value was advertised (Macall *et al.*, 2021). However, consumers were in fact purchasing genetically modified foods if prices were equivalent or cheaper than alternatives (Macall *et al.*, 2021).

4.2 Digital technologies: Automation, robotics, and AI

The adoption of digital technologies is a key opportunity area in agricultural production, given the large volume of data involved and advances in software and computing (Jouanjean *et al.*, 2020; FAO, 2021; McFadden *et al.*, 2022; Phillips, 2023). Characterized as "precision," "smart," "4.0," or "fourth wave," digital agricultural technologies include sensing and monitoring devices, as well as drones, robots, and other automated machines, which are governed by wireless technology, cloud computing, big data and machine learning, as well as the Internet of Things (IoT) (Abbasi *et al.*, 2022; Lassoued *et al.*, 2023). While the panel's focus is on food production, they emphasize that there are also considerable opportunities for digital technologies to support the wider food systems elsewhere along the value chain (Box 4.3).

Box 4.3 Examples of digital technologies across the food value chain

A review by Ferreira & Reis (2023) found that AI and robotics have the potential to improve the operational efficiency of logistics while reducing errors, enabling faster and more consistent delivery of goods to consumers. Such improvements to logistics would benefit producers by making it easier, quicker, and potentially less costly to deliver their products to other markets, while also offering cloud solutions to track and monitor these products (as reviewed in Feng & Ye, 2021). Relatedly, digital technologies may also support reduced food loss and waste across the food system, including in production, although additional research to evaluate this potential is needed (Benyam *et al.*, 2021). These technologies also provide growers with direct access to market data and new avenues for small growers to sell their products (Feng & Ye, 2021; Raiaan *et al.*, 2024).

Digital technologies offer a range of potential benefits for production processes and can support economic sustainability

The digitization and automation of farming activities (including atypical and conventional) has been ongoing since the 1990s, with new practical applications regularly being developed (Leader *et al.*, 2020; Ivus *et al.*, 2021; McFadden *et al.*, 2022). The benefits of digitization are commonly framed around increased efficiency, reduced expenditures on inputs such as fertilizer, water, fuel and herbicides, and lessened environmental impact (Ivus *et al.*, 2021; McFadden *et al.*, 2022, 2023). The current range of digital and digital-assisted tools being used in agriculture encompasses computer and cloud-based data management software, sensors, soil and yield maps and monitors, automated guidance systems (e.g. autosteering devices), automated section control, drones/automated aircraft, variable rate technology, and other robotic devices (Ivus *et al.*, 2021; Abbasi *et al.*, 2022; USGAO, 2024). Regardless of the specific use, the digitization of processes entails the conversion of measurable physical properties into digital data, transfer of the data to accessible storage, and then analysis of the data to inform decision-making (McFadden *et al.*, 2022; USGAO, 2024).

Many digital tools have been developed with conventional agriculture in mind, but others are being developed or modified to assist CEA operations in particular. After all, a key aspect of CEA operations involves monitoring the growing environment, typically involving a wide range of sensors. Misra *et al.* (2022) illustrate an example of a greenhouse environment that includes IoT monitoring and control (Figure 4.1). In this example, sensors for temperature, rain, humidity, imaging, soil, solar radiation, and gas exchange are linked to a cloud-based computing system (database and AI) via monitoring devices (cell phone, computer), to control heating and ventilation systems.

Relevant networks for atypical production could include controls for artificial lighting, nutrient delivery, climate control, CO_2 enrichment, or other industrial processes (e.g., stirring, aeration), depending on the production system (e.g., vertical farm, precision fermentation) (Lakhiar *et al.*, 2018; Bersani *et al.*, 2022; Zhang *et al.*, 2022, 2023; Sharma *et al.*, 2023). While some networks could be local and rely on, for example, a local computer and software for analytics and decision-making, there are substantial advantages to—at minimum—connectivity between the producer and their facility for a remote monitoring and alert system.

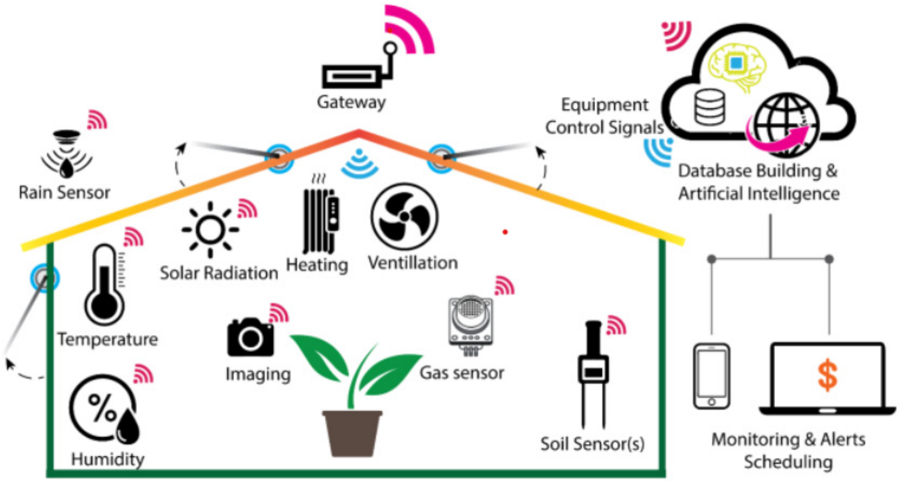


Figure 4.1 An IoT-based automated greenhouse system

To optimize environmental conditions for plant growth, the computing system allows for the analysis of sensory inputs and decision-making regarding controls for heating and ventilation. The cloud-based system also communicates with connected devices so that producers can remotely monitor their facilities.

In greenhouses, for example, one area of active research is digital tools to optimize energy use by modelling energy requirements based on building specifications and outputs from sensors. Research into the area of greenhouse energy modelling is helped by advancements in computing; however, there is a need for these tools to be made accessible to growers, who may lack the specialized knowledge and software to implement these techniques (Iddio *et al*., 2020). Furthermore, the majority of research has focussed on either lettuce or tomato production, and the resulting models may not apply to other crops or crop mixes within single structures (Iddio *et al*., 2020). Nevertheless, the potential to reduce energy costs through optimization processes made available by digital technologies can be critical to CEA producers, given the potentially high contribution of energy to operating costs (Section 5.1).

Data governance frameworks will be needed to address risks for growers related to data portability and cross-border data flows

Perhaps the most important data-related issue for growers concerns who can control, access, and extract value from the data generated by digital technologies (Misra *et al*., 2022; Phillips, 2023). Often, contracts for digital infrastructure and technologies give exclusive data rights to the technology providers (Phillips, 2023). Moreover, agricultural data typically is not protected or regulated by existing data governance frameworks or legislation (Jouanjean *et al.*, 2020; Phillips, 2023), and the power imbalance between growers and technology providers creates risks for growers, as large, vertically integrated technology providers can use their market power to force growers into "data oligopolies" (Jouanjean *et al.*, 2020). Contracts may also limit data portability, which is the ability of growers to transfer their data between technology providers without affecting its usability (Jouanjean *et al.*, 2020). Furthermore, even when the right to data portability is included in contracts, it may be hindered in practice by a lack of interoperability between technology providers (Phillips, 2023). This can lead to lock-in with particular vendors, resulting in dependency on that provider, reduced choice in equipment and service providers, and weakening of the grower's bargaining position in contract negotiation (Jouanjean *et al.*, 2020; Phillips, 2023).

These risks highlight the need to develop robust and enforceable governance frameworks for agricultural data. While jurisdictions such as the United States and European Union have made some progress on the issue of agricultural data governance, Canada has not yet developed a data governance system for agriculture, despite being a major generator of agricultural data (Phillips, 2023).

Automation presents both benefits and risks, and these tools may not be accessible or suitable for smaller or remote operations

Automation is attractive to increase productivity and as a response to labour shortages (AIC, 2021) (Section 5.2), yet the reality of choosing whether (and where) to pursue automation is nuanced. Automation does not necessarily replace labour but redeploys it. In the World Economic Forum's *Future of Jobs Report 2023,* nearly half of businesses surveyed expect the adoption of new agricultural technologies to be a net job-creator (WEF, 2023). The increased use of robotics may also change skills demands, with workers now needing digital skills to manage equipment and software. However, the required upskilling process may be complicated by the shrinking and aging agricultural labour force (Ryan, 2023).

Automation of CEA processes, for example, includes autonomous robot systems that are able to perform a variety of tasks without external guidance or direct human control (Morar *et al.*, 2020; ecoation Innovative Solutions, 2023). These tasks include: managing crops (e.g., plant grafting, grading, deleafing, harvesting) (van Henten *et al.*, 2013); recognizing pests and diseases (ecoation Innovative Solutions, 2022); and monitoring growing media conditions (e.g., pH, electrical conductivity), water, and nutrient levels (Araújo *et al.*, 2021). Key to robotics are navigation and guidance systems, which include machine vision, global navigation satellite systems and a range of sensors, such as optical, inertial and electro-mechanical, as well as electromagnetic and ultrasonic sensors (Bagagiolo *et al*., 2022). These sensors are critical for identifying the targets of tasks—for example, detecting fruits and vegetables for harvest through the use of optical cameras. Additional components of robotic systems depend on the designated task (e.g. fruit grasping systems for harvest or spraying). These systems are becoming increasingly effective, but there are still areas for improvement, including improving operational efficiency through faster processing (Bagagiolo *et al*., 2022). Other examples of robotics research in the testing phase are listed in Table 4.3.

Table 4.3 Examples of robotics technologies in development for CEA

Technology	Proposed benefits	Example reference
Robotic scouting for plant pests	• Important for use with integrated pest management • Enables remote monitoring	Iost Filho *et al.* (2020)
Robotic pollination	• Useful where pollinator populations are difficult to obtain or maintain, where mixed crops require selective pollination	Smith *et al.* (2024)
Robotic crop management including harvest	• Useful where labour availability is limited or cost is high	Morar *et al.* (2020)

The economics of automation are, however, not always straightforward and high costs are a barrier to the commercialization and adoption of automation in agricultural systems writ large (Lowenberg-DeBoer *et al*., 2020). The adoption of technology required for automation raises trade-offs between capital and operating expenditures, since the investments needed for adoption must be recuperated. An EU profile of "future farmers" predicts that CEA operations will not only struggle to permanently automate some roles (e.g., handling seedlings), but also to reliably obtain skilled staff due to the combination of labour shortages and attrition (Bock *et al*., 2020) (Section 5.2).

Overall, the operational expenditures associated with labour need to be weighed against capital expenditures associated with automation (AIC, 2021)—a fact echoed in interviews carried out during this assessment. Interviewees commented that the unit economics of a specific growing business needs to be well understood to properly navigate the advantages and disadvantages of pursuing automation. The large capital expenditures that accompany automation place requirements on the need to scale (potentially rapidly), to maximize revenue and exploit economies of scale.

Such requirements may be inconsistent with the needs and priorities of many growers, including those in northern or remote communities pursuing atypical food production methods.

The next wave of modern agriculture is driven by AI, and recent advances suggest a substantially broadened scope for its application

AI tools provide a means of complex problem-solving in support of automation and allow the leveraging of large amounts of data from multiple streams, in order to solve problems that may otherwise be challenging or intractable (Maraveas, 2023). The potential benefits of AI technologies are vast and can apply to precision agriculture, crop monitoring, yield prediction, automation and robotics, plant breeding and genomics (Hayes *et al.*, 2023; Maraveas, 2023; Bose *et al.*, 2024), among others, with the possibility of eventually influencing profitability as well as environmental and economic sustainability.

The combination of sophisticated algorithms and increasingly inexpensive computation presents several avenues for leveraging existing data to apply AI in support of atypical food production. Several of the main atypical production typologies discussed throughout this report (e.g., CEA, cellular agriculture) often depend on networks of sensors and controls in order to increase efficiency (Shamshiri *et al.*, 2018; Sharma *et al.*, 2023). AI supplements the digitalization of such processes with the potential to also automate decision-making based on the ongoing accumulation of increasing quantities and varieties of data (Fountas *et al.*, 2024). Focussing on CEA, example applications include harnessing AI for the control of lighting, water, ventilation, nutrition, humidity, and CO_2 levels (Maraveas, 2023) (Figure 4.1; Section 2.2), as well as using AI to manage diseases and pests (Rustia *et al.*, 2022), perform visual quality assurance during and after harvest (Lee *et al.*, 2020; Albert-Weiss & Osman, 2022), in addition to supporting other strategies to optimize yields and food safety (Zhu *et al.*, 2021; Ojo & Zahid, 2022).

Foundation models are an emerging new paradigm for using AI with broad capabilities and increasing accessibility for non-specialist users

AI is not monolithic but represents a family of different machine-based technologies that combine software and data to achieve an objective (Russell *et al.*, 2023b). Its various implementations (e.g., machine learning, deep learning) have been applied toward executing various tasks in CEA as described earlier, as well as in agri-food more broadly (Kutyauripo *et al.*, 2023). In typical examples, specialized AI models are elaborated and optimized toward well-scoped and narrow tasks (e.g., lighting control) for the purposes of automation. Recent advances in foundation models, however, could pave the way for an expanded role for AI in agri-food.

AI-based foundation models have the potential for disruption across society and the economy. These models can be multimodal, meaning that they accept and output several types of data (e.g., prose, audiovisual data, software code) (Raiaan *et al.*, 2024). As they continue to be improved and scaled, foundation models have demonstrated non-linear progress and improvements across several benchmarks relating to the execution of narrow tasks (e.g., Katz *et al.*, 2024), while demonstrating human-like reasoning and communication capacities (Hagendorff *et al.*, 2023; Jakesch *et al.*, 2023). Foundation models can be used through a conversational interface, lowering the barrier to use by reducing the need for information technology expertise. In agriculture, this property has enabled scientific information to be shared in plain language, and has also supported data-informed decision-making, and the provision of advisory services (Tzachor *et al.*, 2023). By integrating data sources, these models can calculate accurate, real-time insights—crucial for efficient crop management, disease prevention, and yield optimization—and communicate them to operators (Fountas *et al.*, 2024; Raiaan *et al.*, 2024).

Training models on vast quantities of agricultural data could, moreover, establish agricultural foundation models able to provide human operators with planning for such complex tasks as pest management, or plant health monitoring more broadly, rather than support discrete components of those tasks (Li *et al.*, 2024). For example, while in past applications AI would be responsible for carrying out one or more pieces of analysis (e.g., identifying pest presence), agriculture foundation models enable the technology to instead manage complex tasks across a product life cycle with relatively high autonomy, with business implications for product development, marketing, and labour, among others (Box 4.4). Major multinational information technology firms are increasingly active in offering AI-based tools and services to support food producers in various tasks (AWS, 2024; Richter, 2024).

Box 4.4 Simulating real-world problems with AI

Innovations in AI are fast-moving and hinge on advances intrinsic to AI as well as on the increased availability of data and developments in related technologies. This may give rise to new services and tools for food producers. For instance, combining and monitoring various forms

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of data obtained through sensors and other IoT devices across the production life cycle allows the creation of "digital twins" (Verdouw, 2022; Helmy *et al.*, 2024). These replicate a real-life physical growing environment in a virtual form—updated nearly in real-time—allowing producers to not only monitor their operations remotely but also simulate future outcomes or recommend actions (Escribà-Gelonch et al., 2024).

Adjacent technologies such as augmented and virtual reality could be combined with AI and digital twins to underpin new methods for training, simulation, and support services (Caria *et al.*, 2019; Fountas *et al.*, 2024). For example, efforts are ongoing to combine virtual reality with greenhouse simulations (Kim *et al.*, 2021; Slob *et al.*, 2023). These initiatives successfully replicate entire three-dimensional greenhouse structures containing simulated plants (based on real historical growth data), allowing users to visually explore and interact with the greenhouse contents and processes (Slob *et al.*, 2023). In this way, education and training resources could be delivered without necessarily having access to a physical facility, where the consequences of growing decisions can be stimulated *in silico* at speeds no longer limited by physical plant growth (Slob *et al.*, 2023; Escribà-Gelonch *et al.*, 2024).

Opportunities exist for digitalization and AI in Canadian agri-food, but capacity and incentives may be lacking for small growers

Canada continues to be a world leader in AI research, with a track record in producing discoveries and highly skilled workers in AI-related fields (ScaleAI, 2023); however, the adoption and commercialization of AI lags despite a well-developed research ecosystem. Concerns about AI adoption in Canada have been substantiated in analyses of technology use patterns in Canadian firms, not limited to the agri-food sector (Lockhart, 2023). An AI compute shortage[21] (Dobbs & Hirsch-Allen, 2024) has been identified as a key barrier to adoption, along with other practical business challenges relating to the recruitment of skilled labour and upfront investments required for adopting AI (StatCan, 2023a). Additionally, a lack of knowledge about AI capabilities—alongside related inabilities to identify relevant business needs—has been identified as a core challenge in adoption for small firms (Lockhart, 2023).

21 Budget 2024 has committed federal investments towards addressing this deficit (GC, 2024).

Scant evidence exists to understand how the above trends observed in the broader Canadian economy translate to the agri-food sector. Agriculture is excluded from the Statistics Canada Survey of Digital Technology and Internet Use (StatCan, 2021) underpinning Lockhart (2023), and the limited data on the agricultural sector found in the Statistics Canada 2023 Survey of Advanced Technology suggests there are low AI technology adoption rates across agriculture (StatCan, 2023b). Moreover, most of the surveyed firms indicated limited intentions of integrating AI and identified the technology as "not applicable" (StatCan, 2023c). A separate 2022 report on digital adoption more broadly identified the agriculture and fishing sectors as ones that lagged in adopting digital technologies over a fifteen-year observation analysis window, despite a good track record for technology adoption overall (Abuallail & Vu, 2022). Various reasons are proposed for this lag, ranging from the low availability of crucial supporting hardware (e.g., robotics, IoT), to the prevalence of low-cost agricultural labour (Box 5.2).

Technology use is also uneven across Canadian farming operations. For example, oilseeds, grains, and other high-value or widely-produced field crops are the focus of many of the companies that provide precision agriculture products and services in Canada (Ivus *et al.*, 2021), as opposed to the products grown in CEA operations. Initiatives to help small operators adopt and effectively use new technologies may enable a greater number of farms to take advantage of the benefits digital technologies provide. High data infrastructure costs—from sensors to data platforms—may be a barrier to adopting digital agriculture technologies and AI, particularly for smaller growers (Phillips, 2023). High costs could offset the economic gains from increased productivity resulting from these technologies (Misra *et al.*, 2022). Lack of high-speed internet access can also hinder the adoption of digital agriculture technologies, particularly affecting growers in rural and remote areas (CCA, 2021; Ivus *et al.*, 2021; McFadden *et al.*, 2022) (Section 6.1). Initiatives geared to assist businesses in identifying opportunities to adopt AI and design implementation strategies (CDL, n.d.), or provide funding toward capital expenses or hiring skilled labour (ISED, 2024; Mitacs, 2024), may begin to address what ScaleAI argues is a "demand-side" problem in Canadian industry (ScaleAI, 2023).

> The panel highlights the opportunities across the sector in harnessing AI, with potential benefits for conventional and atypical producers alike.

Growers require better information on the costs and benefits of different technologies in different contexts if they are to make informed decisions

(McFadden *et al*., 2022). Similarly, inclusive approaches for developing AI and other digital tools could also help to promote adoption while mitigating risks (Tzachor *et al*., 2022) (Box 4.5). The utility of AI will be different for small farms as compared to large farming operations, arguably with implications for atypical food production. However, the panel wishes to highlight the opportunities across the sector in harnessing AI, with potential benefits for conventional and atypical producers alike.

Box 4.5 Implications of deepening integration of digital technology and food production

Digital technologies bring certain risks that differ from those arising from other uses of new technologies in food production (e.g., health risks from pest-control agents). Some of these relate directly to operations and business. For example, cyberattacks may be used to steal data or IP, or to interfere with or damage vital infrastructure (Yazdinejad *et al*., 2021). The use of sophisticated AI systems to manage several operations of production could, under these circumstances, represent a "centralized point of failure" that is vulnerable to cyberattacks (Tzachor *et al*., 2022). This can not only harm crop yields for growers, but also result in loss of business or reputation (Misra *et al*., 2022).

Unequal distribution of the benefits of AI also has the potential to widen existing gaps between digital haves and have-nots, with additional broad implications for the labour market (Sparrow *et al*., 2021). AI and automation could contribute to reduced opportunities for farm labourers, particularly for migrant workers, by eliminating labour outright or displacing it towards high-skilled roles (Rotz *et al*., 2019; Tzachor *et al*., 2022) (Section 5.2).

Beyond business, the promise of increasingly powerful AI applied to increasingly broad tasks brings certain ethical and social risks. For example, introducing a sophisticated foundation model acting as a local knowledge expert has risks associated with the "black box" nature of many AI models, meaning they cannot provide explanations or interpretations of their outputs (EPRS, 2023). This has practical and cultural implications for the relationship between the food production process and growers, who may lose agency (Sparrow *et al*., 2021). There are also concerns related to bias (EPRS, 2023), since commercial incentives dictate that models are developed for industrial input-intensive farming practices, and trained on the associated data (Sparrow *et al*., 2021). There may be incompatibilities with other systems,

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such as Indigenous growing practices, which involve place-based traditional ecological knowledge and polyculture techniques (Sparrow *et al.*, 2021; Tzachor *et al.*, 2022). The climate change impacts of AI also raise concerns (Sundberg, 2023; Crownhart, 2024), since the energy and water resources required both for operating AI models and building the related infrastructure are rapidly growing as models increase in sophistication (Ren, 2023; IEA, 2024). These requirements need to be considered alongside the sustainability improvements obtained through efficiencies unlocked by these tools.

4.3 Conclusion

Food production based on atypical technologies holds promise for supporting the diversification of Canada's food system, but the economic and environmental sustainability of these technologies face various challenges. As discussed in earlier chapters, while considerable research is related to core CEA and atypical protein technologies seeking to address some of these challenges, enabling technologies also have a critical role. The benefits of many enabling technologies are already well established, and their expansion in atypical production operations may bolster production and help overcome some of the key issues that act as barriers to success.

In this chapter, the panel focussed on genomics and digital technologies, given their potential beneficial impact. Genomics opens the door to tailoring variants to the specific conditions of CEA, improving yields and expanding the range of foods that can be grown in indoor conditions. This can include foods with greater nutritional value or important cultural significance. While genomics targets the plants themselves, digital technologies provide opportunities to improve practically all aspects of the production life cycle. For example, robotics and automation can reduce the need for labour and increase productivity, while AI creates opportunities to use data in ways that help support operations and improve efficiency. At the same time, there are barriers to adoption, including high upfront costs, along with cybersecurity risks to be mitigated. While digital technologies are increasingly being used across the agri-food industry more broadly, there is considerable room for growth. Among these are various implementations of AI that might be further integrated into atypical production, raising opportunities but also risks that will require careful consideration.

In the next chapters, the panel shifts its focus away from technologies and considers other elements that have a direct influence on whether atypical production operations will be successful. These elements include the enabling environment (Chapter 5) and the policy and regulatory landscape (Chapter 6).

5

Enabling Environment

Chapter findings

- Energy is one of the top operational costs for CEA, and the efficiency of facility components and the regional price for energy strongly influence the economic sustainability of operations.
- Atypical food production methods require infrastructure inputs (e.g., energy, water, internet) that can be less reliable or affordable in northern, remote, or Indigenous communities than in other regions of Canada.
- Producers face high start-up costs for technology in a financing environment geared toward field-based production. Novel approaches for funding and financing could lower their risk.
- CEA requires both manual and highly skilled labour. While labour shortages and skills mismatches complicate recruitment, automation and robotics add to upfront costs.

Food production takes place across diverse social and geographical settings. The technologies used in local food production do not operate in isolation and are ideally embedded within communities and guided by local needs while drawing on local resources. Whether atypical food production methods are adopted will depend on innovation and technical accomplishments such as those described in earlier chapters, but also on ensuring access to the needed infrastructure, finances, and labour. This chapter provides a review of the supporting physical infrastructure required to operate atypical food production facilities, including energy, water, and internet connectivity, as well as some discussion on logistics and transportation. Also explored are economic considerations, including financial tools and supports for growers, and labour issues in CEA and agriculture more broadly.

5.1 Supporting infrastructure

Many of the atypical production technologies discussed in this report are intended to support year-round, local food production in Canada, including in remote and isolated locations. Support for such production systems requires infrastructure beyond the facilities themselves. For example, differential access to high-speed internet has implications for the ability to adopt the digital technology solutions in agriculture discussed in Chapter 4. Similar challenges exist for essential food system infrastructure, such as affordable and reliable energy sources and clean water, as well as storage, transportation, and distribution facilities. Although many of the examples of supporting infrastructure provided in this chapter focus on CEA applications, similar concerns hold for atypical protein production. The integration of cellular agriculture into Canada's food system will depend on the availability of continuous and resilient sources of energy and inputs, as well as associated infrastructures, including supply and distribution systems (Soice & Johnston, 2021).

> The technologies used in local food production do not operate in isolation and are ideally embedded within communities and guided by local needs while drawing on local resources.

5.1.1 Energy

The energy demands of CEA systems differ depending on various factors, such as facility size, lighting, HVAC, external environmental conditions, and the plants it is producing. However, as Sabeh *et al.* (2022) observed, most of the energy use reported in the literature for CEA facilities is based on modelling estimates and operational assumptions, rather than in situ measurements. The deficit in accurate information makes it difficult to estimate the total energy demands of CEA facilities, and further compare them to other modes of production. This evidence gap is more acute for some types of atypical protein; the energy demands of a cultured meat facility are more difficult to estimate than CEA, given that none yet operate at a commercial scale.

Across Canada, the cost of purchased energy—and the sources used to supply that energy—vary substantially

Energy expenditures will depend on the location of the facility, with electricity costs being a major consideration for growers and operators (iFarm, 2023). Electricity costs vary substantially across the country, and while some provinces and energy providers have lower rates for commercial and industrial operations, others charge businesses rates higher than those set for residential use (Bishop *et al.*, 2020). Notwithstanding that rates do not reflect the full cost of electricity,[22] average large industrial rates vary by over a factor of two across major Canadian cities (with Edmonton highest and Montréal lowest) (NRCan, 2023). These rates typically range from 5–15¢/kWh whereas in Nunavut commercial rates are substantially higher and can be above 50¢/kWh (QEC,

22 Tiering as well as other tariffs and subsidies vary across providers and will factor into total costs alongside consumption (Bishop *et al.*, 2020).

2023). Based on the average monthly consumption of a commercially available container farm unit (Growcer, n.d.), such rate differences can amount to hundreds of dollars per month in electricity costs.

Each energy source is associated with different emissions profiles. Notably, Nunavut relies almost entirely on diesel to meet end-use demands, as do many remote communities in the other territories (CER, 2023). Across the country, demand is met by a mix of sources, including natural gas, nuclear, biofuels, and, primarily, hydroelectricity (CER, 2023). Implementation of atypical food production facilities in locations that rely on fossil fuels may not be feasible given the additional burden on already taxed energy supply (Wilkinson *et al.*, 2021). The feasibility of non-fossil fuel energy sources, such as solar, wind, or biofuels, varies by location in Canada (Thompson & Duggirala, 2009; Prabatha *et al.*, 2020; Dehghani-Sanij *et al.*, 2022). Life cycle assessments are required to have a fulsome picture of the potential environmental benefits or challenges of atypical food production across Canada, since these include whole supply chains from both imported markets and local supply, as well as the resources used in building materials and other embedded inputs (Wilkinson *et al.*, 2021).

Energy is a major component of the operational costs for CEA facilities

Energy is often the second-largest operational expense following labour (Lubna *et al.*, 2022). Energy costs are a key difference in the operational costs between field agriculture and CEA, sometimes representing a third of expenses (Nicholson *et al.*, 2020, 2023). Vertical farms use substantially more energy than greenhouses (Eaves & Eaves, 2018), and the total operating cost per square metre of growing space in a vertical farm in the Netherlands has been estimated to be up to five times greater than for a high-tech greenhouse (Rabobank, 2018 as cited in Butturini & Marcelis, 2020). Notably, stacked vertical lighting can account for up to two-thirds of energy costs for vertical farms, with costs for HVAC control comprising the rest (iFarm, 2023). CEA business operators interviewed for this assessment were unanimous in expressing that the greatest challenge that they face is obtaining reliable and inexpensive energy inputs for their production operations. This issue applies to large-scale operations seeking to deliver local food at a price point competitive with open-field agriculture. It is even more challenging for growers operating in remote regions due to the high electricity costs in those locations.

The environmental sustainability of atypical production depends on energy sources

As environmental sustainability is comprised of considerations for water, land use, GHG emissions, and other components, no one facility type or location will fulfill sustainability goals for each environmental outcome. Though some facilities may use less water and land than field-based operations, the trade-off is greater GHG emissions (Nicholson *et al.*, 2020). Nonetheless, CEA operations may be able to reduce their environmental footprint by using renewable energy sources. For example, when considering total supply chain costs, if renewable energy sources are not used, urban and peri-urban CEA is more expensive and has a higher global warming potential than field-grown lettuce, despite the long distances the latter has to travel to reach consumers. By using variable renewable energy sources, "CEA can match the standardized energy cost obtained in field operations, and improve upon the environmental performance" (Nicholson, unpublished manuscript).

Alternative energy sources are especially important in the wider context of emissions reduction efforts like carbon pricing. The potential impact of carbon pricing was undermined by successful lobbying from the greenhouse sector that resulted in an 80% rebate for federal carbon pricing; such efforts emphasize the critical need for economically viable energy alternatives (FIN, 2018; Hansen *et al.*, 2020).

5.1.2 Water

Some proponents of CEA emphasize a greatly reduced water burden when compared to conventional field crops (e.g., Benke & Tomkins, 2017). This may be true for the application of irrigation water (Nicholson *et al.*, 2020, 2023); however, the net water consumption of the entire CEA supply chain and associated environmental impacts have yet to be defined or widely studied. These will vary by the location and type of CEA system (Gómez *et al.*, 2019). Urban agriculture operations often promote water use reduction narratives (generally linked to hydroponic systems), implying lower water usage than conventional field agriculture; however, this claim is often unsubstantiated, with no information on water consumption per plant reported (Parkes *et al.*, 2022). Regardless of the exact numbers, CEA operations do require a source of water to operate and will be impacted by the quality of that source (Dorais *et al.*, 2016). For example, if the water source being used by a CEA facility is high in a particular mineral, this could impact fertilization and other water treatment needs (Zikeli *et al.*, 2017).

Reclaimed water sources have been offered as a solution to increasing efficiency in CEA

Typical operations in urban or peri-urban settings will draw on public utility providers to obtain water, but for those producers as well as for producers without access to such supplies, the potential use of reclaimed water can be appealing to reduce costs and increase operational circularity. However, although reclaimed water can be used to support CEA, unless properly cleaned, it can introduce pathogens to otherwise clean systems. For example, Lopez-Galvez *et al.* (2014) tested both irrigation water and reclaimed water for tomatoes grown hydroponically and found the prevalence of *Salmonella* spp. to be 8% and 63%, respectively. Properly cleaning reclaimed water or wastewater is therefore necessary to defend against contamination, but is also energy intensive (Gómez *et al*., 2019). Closed-loop hydroponic systems reuse water and nutrient solutions for several cycles or for a longer growing period (Son *et al*., 2016). They may be further optimized by implementing a cascade system which waters secondary plants using drainage solution from primary plants (Elvanidi *et al*., 2020). This system results in 30% less fresh water consumption for secondary plants as compared to those irrigated with fresh water, and 40% less disposal of nitrate than with a monoculture (Elvanidi *et al*., 2020).

Some consumers and growers exhibit concerns surrounding the use of reclaimed water due to the potential presence of pathogens or chemicals (Savchenko *et al*., 2019; McOmber *et al*., 2021, 2023). Although the underlying surveys in these studies were not carried out in the North, the existing historical and cultural relationships around water consumption and food safety in that region suggest that similar aversions could arise regarding the use of reclaimed water for CEA in those communities (Ratelle *et al*., 2022).

Critically, some areas of Canada may not have sufficiently clean water for irrigation, in addition to not having water safe for human consumption. Several Indigenous communities in Canada rely entirely on trucked-in water or remain under boil-water advisories, limiting the availability of water as a resource for CEA facilities in certain regions (Natcher *et al*., 2021). Although it may not need to be at the quality level for human drinking water, irrigation water for CEA should still be free of human and plant pathogens to ensure sufficient productivity and product safety (Dorais, 2019). This may require filtration, disinfection, desalinization, additives to manage pH, and other adjustments, which may be both cost and energy intensive (Dorais *et al*., 2016; Dorais, 2019). It is therefore possible to ensure a clean supply of freshwater for CEA regardless of current water quality conditions in a community, but such a supply demands additional resources for the building, operation, and maintenance of supporting infrastructure. Such infrastructure may not be an appropriate use of resources in communities that do not have reliable access to safe drinking water.

5.1.3 High-speed broadband

Reliable, high-speed broadband internet is required for atypical food production facilities to access the benefits of digital technology tools. High-speed networking capacity may be needed to ensure effective management of various sensors, or access to necessary databases or modelling resources offered through AI (Section 4.2). For example, a variety of connectivity challenges exist for the industrial application of the IoT (Li *et al.*, 2017). Different components or systems have different critical value for the production system, which adds complexity to their integration for analysis and decision-making. Network latency and fault tolerance are similar challenges for complex interconnected systems, in which different components must communicate with each other smoothly and without delay, and for which there must be mechanisms in place to ensure failures in one part of the system do not compromise the integrity of the whole. Moreover, cybersecurity will be an ongoing challenge for any connected system (Box 4.5).

Accessing high-quality internet is a challenge in many rural, remote, and Indigenous communities

According to the Canadian Radio-television and Telecommunications Commission, broadband internet with unlimited data and speeds of at least 50 Mbps download and 10 Mbps upload is available in only 62% of rural communities in Canada (CRTC, 2023). This means that roughly 40% of rural and remote areas in Canada lack the internet speeds necessary for digital agricultural technologies such as sensors and data platforms (CRTC, 2023; Phillips, 2023). Reliable internet service depends on a variety of factors, including stable energy sources, ICT infrastructure (e.g., towers, fibre), system redundancies (in the event of outages), and transportation infrastructure (for maintenance and repairs) (CCA, 2021). Low Earth orbit satellite infrastructure can provide connectivity for remote communities; however, there are cost, lifespan, and reliability considerations (CCA, 2021) that can impact their value for producers reliant on connectivity to maintain real-time environmental conditions in their facilities.

5.1.4 Importance of logistics and transportation

Outside of the physical infrastructure for producing food, logistical considerations (e.g., processing, packaging) and transportation impact the attractiveness of atypical food production, especially CEA. Planning and optimizing logistics and transportation also depends on facility location and market proximity.

Localization of food production in Canada may support resiliency while not necessarily being more environmentally or economically sustainable

The perception that local food production will be more economically and environmentally sustainable may not be true in all cases. For example, urban and peri-urban CEA facilities in and near New York City and Chicago were not found to be more environmentally friendly than field-based agriculture for lettuce, even when factoring long-distance transport from California (Nicholson *et al.*, 2020, 2023). Economic sustainability is another key consideration; land values may differ considerably between rural locations (field-based agriculture) and urban or peri-urban locations that are more proximal to markets (Nicholson *et al.*, 2023). This complexity suggests that producers will need to "optimise trade-offs between land and transportation costs … for costs to be more comparable between field and CEA lettuce supply chains" (Nicholson *et al.*, 2020). Having said this, local food production could offer stability of access to food for northern communities impacted by supply chain failures, such as transportation issues (Fressigné *et al.*, n.d.), provided that supply disruptions do not also affect local production inputs. For instance, the 2012 flooding of the Alaska Highway was named as a key example of a situation in which local, community-based food production systems can be beneficial (ISFS *et al.*, 2014). Similarly, during major supply disruption events such as the COVID-19 pandemic, local food production provided alternatives in light of the wide interruptions across the food production industry (e.g., meat-packing) (Thilmany *et al.*, 2021). Local food production cannot solve food insecurity on its own but can contribute to resilience in the overall food system by providing options (Wood *et al.*, 2023).

Atypical food production technologies are part of local, regional, and global food systems

Production is only one component of the larger food system (Figure 1.1). Packaging, storage, and distribution are also needed to ensure that food produced atypically reaches the market and consumers, with corresponding infrastructure requirements. There are also storage and transportation considerations in the construction and maintenance of facilities, particularly for those planned or in operation in remote and isolated communities in the North (Avard, 2015). Concerns include both transportation costs for building materials and the potential for delivery delays (Avard, 2015). Similarly, in the experience of one member of the expert panel, logistical challenges can threaten reliable access to key production inputs (e.g. seeds) and prevent the procurement of timely and appropriate supports for facility maintenance and repairs.

5.2 Economics and labour

Beyond core infrastructure needs, atypical food production requires financial and human resources to launch and maintain operations. For example, significant funding may be needed to acquire land, equipment, and inputs. Attracting the general and specialized labour required to establish production may also be a challenge as there is a widespread labour shortage in agriculture (AAFC, 2023c). Furthermore, atypical production facilities may require skills not developed in typical training programs.

5.2.1 Economic considerations

The economic sustainability of atypical food production is a key determinant of the feasibility and appropriateness of the accompanying technologies. In commercial settings, struggles arise due to the challenging combination of high start-up costs, narrow profit margins, and the vagaries of market access and consumer preference, among other factors (Young *et al.*, 2022; de Sousa & Shanker, 2023; Peters, 2023). Atypical food startups are also exposed to macroeconomic trends, such as increasing interest rates and market volatility, causing their operating expenses to increase while impeding access to capital (de Sousa & Shanker, 2023; McKinsey & Company, 2024). In both commercial and non-profit settings, the ability to secure appropriate financial support and suitable labour—while managing costs—is essential for establishing and maintaining atypical food production facilities.

Economic barriers are of particular importance for circumpolar agriculture in Canada. Seguin *et al.* (2021) interviewed participants and interested parties in the northern agricultural landscape to determine key barriers to the expansion of circumpolar agriculture. Although emphasizing that many barriers were important and intertwined with one another, the most significant were economic barriers, such as a limited capacity to recoup capital costs, high operating costs, and difficulties securing funding. These results were echoed in research by Wilkinson (2023) and Wilkinson *et al.* (2021), in which initial investment costs were noted as a barrier to CEA adoption by northern communities.

Support for atypical food production in Canada is largely uncoordinated, and new entrants to the field can face barriers to securing adequate financing

The development and adoption of atypical food production methods face several barriers relating to funding and financing. The primary source of funding for new technology development and adoption in Canada is public funds (AIC, 2017a, 2021). At the same time, some argue that agricultural R&D funding lacks coordination (AIC, 2017b). The main incentive for R&D and technology adoption on a business level is provided through tax credits, which tend to benefit larger businesses as compared to smaller operations, and high start-up and operating costs (Box 5.1) constrain the funds available for R&D (AIC, 2021). Moreover, in comparison to other sectors such as health, Canada has limited private investment in the agri-food sector, and large institutional investors (e.g., major pension funds) have mostly retreated from investing in agri-food R&D (AIC, 2021). Wilkinson (2023) and Wilkinson *et al.* (2021) raise this issue in the context of CEA in the North, where initial investment costs pose a substantial barrier to adoption because agri-food funding is not designed with alternative production in mind. Individual funding programs based on "challenges" have been deployed to spur technological innovation in food (Impact Canada, 2023; Homegrown Innovation Challenge, n.d.); however, these focus on proof-of-concept and implementation and would need to be complemented by supplementary funding sources to establish full-fledged businesses equipped for long-term success.

Box 5.1 Opportunities to reduce economic barriers beyond start-up

Governments can use various tools and approaches to lower the economic burdens of operations. These may be of particular relevance for atypical food production because of the specific needs and high operating costs of those operations (particularly in the North) and the potential challenges in accessing support mechanisms available to conventional agricultural producers. Among these, mechanisms to lower tax burdens are common and can apply to several aspects of a growing business. For example, property tax reductions on farmlands are available to some growers in Ontario (AgriCorp, 2023), and this could be extended to CEA operations. The Canadian Federation of Independent

(continues)

(continued)

Businesses has proposed tax credits for training (including informal training) or for hiring students as a means for businesses to fulfill their part in developing the workforce while reducing operational expenses (Brown & Yoo, 2022).

Targeted rebates and subsidies can also be employed to encourage production using novel technologies or in remote locations. The Quebec government's *Programme d'aide financière pour favoriser le développement des serres* offers a two-pronged approach, by providing rebates on electricity costs of up to 40%, as well as financial support toward the launch, expansion, or electrification of a greenhouse operation (MAPAQ, 2020).

Northern and remote producers face unique operating costs for which targeted measures could be helpful. In the United States, the reimbursement transportation cost payment program run by the USDA Farm Service Agency allows "geographically disadvantaged" producers to recover some of these costs (USDA, 2023b). The Canadian federal government does not offer analogous programs for northern, remote, or Indigenous growers, but does have cost-shared funding opportunities specifically for those eligible for the Indigenous Agriculture and Food Systems Initiative (AAFC, 2018).

An additional issue for new entrants to the agricultural sector is that Canadian producers have a substantially smaller share of national commercial lending when compared to the global average (Stackhouse *et al.*, 2019). Moreover, the extent to which credit and funding programs apply to atypical food technologies is not always clear, leading to the perception, whether correct or not, that these programs are geared toward conventional production (Hui, 2023). For example, the *Canada Agriculture Loans Act* (CALA) Program offers avenues for Canadian producers (AAFC, 2020), as do several options made available through Farm Credit Canada (FCC, 2024b). Although greenhouses are eligible for CALA, other types of CEA are not necessarily within scope (AAFC, 2020). In the United States, USDA Farm Loan Programs provide similar direct guaranteed loans, but tailored to specific needs, such as starting a new business or offsetting operating expenses (USDA, 2023c). Characteristics vary according to the type of loan, with low-interest rate emergency or downpayment loans made available to provide relief to farmers who have experienced unexpected challenges or who are seeking to finance the purchase of land (USDA, 2020a). Moreover, the USDA has explored programs directed to alternative production by orienting the Microloan programs to "non-traditional and specialty" operations, including many typologies of CEA (e.g. vertical growing) (Rogge, 2019; USDA, 2020b).

Industry studies drawing primarily on food producers in the United States reveal that, for commercial CEA operators, venture capital and private funding are the primary sources of financing (Agritecture Consulting & Autogrow, 2019; CRETAU, 2020). Investing in vertical farming and other types of CEA is perceived as risky due to uncertainties surrounding the socioeconomic realities of building and running facilities (see references in de Oliveira *et al.*, 2022).

Alternative financial tools tied to positive environmental impacts could spur greater sustainability in atypical food production technologies

For companies or initiatives that aim to address climate change, among other social or public goods, sustainable finance is an alternative approach to financing. In this paradigm, financial returns on investment are considered alongside performance in environmental and social areas (ECCC, 2019). The United Nations Environment Programme identifies three pillars for creating a policy environment that enables the application of sustainable finance principles to food systems, based on:

- developing risk frameworks across the value chain to manage chronic and emerging risks;
- altering incentive frameworks to better redirect existing and new capital flows toward sustainable production; and
- fostering effective market signalling to influence the behaviour of market participants through, for instance, disclosure requirements around environmental performance.

(UNEP, 2023)

Sustainable finance approaches can theoretically be applied to most conventional financing instruments in agri-food, including supply chain finance, loans, and bonds (Field to Market, 2022). In practice, incentives to support reduced GHG emissions (e.g., carbon pricing) may prove a barrier to entry in locations where clean energy is not available.

Blended finance has also been identified as having promise for spurring transitions toward sustainable agriculture, and could follow sustainable finance principles (Havemann *et al.*, 2020). Blended finance combines financial instruments (e.g., debt, grants, insurance) from public, private and philanthropic sources to leverage their respective strengths (Havemann *et al.*, 2020). Challenges with public money include that it is disbursed slowly and carries several restrictions, while private money can potentially be accessed quickly, but similarly carries requirements and expectations concerning financial returns (Field to Market, 2022). Philanthropic resources can be flexible and tend to have mission-driven mandates, with fewer explicit requirements than public or private funds (Field to Market, 2022). When successful, a blended finance strategy leverages public and philanthropic funds to attract greater private investment through de-risking.

5.2.2 Labour challenges

The agri-food labour force in Canada is confronting several simultaneous issues that limit sectoral growth, including a growing labour shortage and an aging workforce. The Canadian Agricultural Human Resource Council (CAHRC) estimated that over 28,000 agriculture jobs went unfilled in 2022, and that a quarter of the 2022 workforce could retire by 2030 (CAHRC, 2023). A 2022 survey by the Canadian Federation of Independent Business (CFIB) found that half of surveyed small and medium agri-businesses had to restrict their output or service offerings since they were unable to adequately staff their operations, contributing to lost sales (Brown & Yoo, 2022).

Despite increased enrollment in agricultural undergraduate programs, demand for skilled graduates was found to still be growing; as of 2017, the Ontario Agricultural College found that there were four jobs available for every graduate in Ontario's food and agriculture sector (OAC, 2017). In the panel's experience, academic program enrollment rates are not keeping pace with increasing demand due to widespread misconceptions about the nature of agricultural work; most work in the agricultural sector occurs outside the farm gate, which runs counter to popular perceptions.

Labour shortages are worsening in the agri-food sector and may be heightened for atypical food production

Persistent and worsening labour challenges have been linked to several global agri-food trends, such as the decline in family labour and a rise in hired foreign labour (Box 5.2) or, increasingly, automation (Section 4.2). A 2023 CAHRC survey found that a third of employers did not receive any applications from Canadian residents during the previous hiring season (CAHRC, 2023). The CFIB also reports a larger number of new immigrants becoming involved in agriculture compared to other industries (Brown & Yoo, 2022). The demand for foreign labour is projected to grow, while the supply of domestic labour is expected to shrink (CAHRC, 2019). COVID-19 revealed the dependence of Canada's agricultural industry on migrant workers, with farmers expressing concerns over border closures and travel restrictions (Hastie, 2020).

Provincial data collected by CAHRC indicate that location is an important factor: agricultural labour vacancy rates differ by nearly a factor of two across Canadian provinces (from 12% in British Columbia to approximately 4.5% in Saskatchewan and Newfoundland and Labrador) (CAHRC, 2024). One CEA business operator interviewed for this assessment stated that basing their business in a different province less than 50 km away would improve their access to labour due to combined geographic, demographic, and policy considerations.

Box 5.2 Temporary foreign workers contribute essential labour

In Canada, the number of temporary foreign workers (TFWs) overall increased by over 30% from 2017–2023 (StatCan, 2024c). Many of these workers are employed in agriculture. Leamington, Ontario, known as the "greenhouse capital of North America," draws more than 10% of Canada's total migrant farm workers; these workers make up one-sixth of the town's population at peak farming season (Mojtehedzadeh *et al.*, 2017). The mayor of Leamington stated: "I don't think the greenhouse industry would exist if it wasn't for the farm worker program. There just wouldn't be the manpower to make it happen" (Mojtehedzadeh *et al.*, 2017).

Foreign workers are typically involved in general farm labour, such as harvesting. They are strongly valued for filling essential roles where labour shortages are most acute, and work conditions are most challenging (Brown & Yoo, 2022). R&D efforts dedicated to automating tasks carried out by TFWs using robotics and AI are ongoing (Section 4.2), but a sustained demand for general farm labour is expected (Brown & Yoo, 2022). The practice of meeting labour needs through migration is cemented in the Canadian agri-food labour market, and is further supported and incentivized through policies and programs such as the Seasonal Agricultural Workers Program (SAWP) between Mexico and Canada (GC, 2015), as well as the Agri-Food Pilot and Rural and Northern Immigration Pilot (GC, 2020b,c).

Attracting foreign workers is not without challenges, however. Despite their significant contribution to Canadian agriculture, in most cases, workers cannot apply the time spent in Canada toward permanent immigration status (Hastie, 2020). Another barrier to attracting and retaining seasonal migrant workers may be found in the parameters of the TFW program. Surveyed employers emphasized the following challenges: an overly complex, opaque, and inconsistent application process; lack of available and affordable housing; and inequitable wages, along with an inability for employers to reward experience and performance (AAFC, 2023c).

CEA operations are not exempt from agricultural labour-related challenges (Agritecture Consulting & Autogrow, 2019), since manual labour is required for harvesting and packaging roles, among others. Interviews with CEA practitioners for this assessment corroborated that a shortage of skilled labour is a key issue, noting that there are difficulties in finding talent and a corresponding need for high compensation for CEA operations. Recruitment issues identified for conventional agriculture relating to working conditions and isolation in rural communities could be exacerbated in the North and remote areas (Ryan, 2023). In the experience of one panel member, recruitment and retention are both key challenges in their community. There is frequent turnover due to members leaving the community for extended periods (e.g., for education), and the limited time that collaborators from research institutions can remain on-site.

While data suggest that CEA is succeeding at attracting and recruiting a younger workforce—and one that is new to agriculture—the research is skewed toward facilities in urban or peri-urban rather than rural or remote environments (Agritecture Consulting & Autogrow, 2019; CRETAU, 2020). Ryan (2023) suggests that negative perceptions of the agri-food sector could be countered through technology adoption that emphasizes opportunities for up-skilling and highlights new or different career pathways. This may be relevant for atypical production, which can be presented as a new and innovative way to produce food. However, technology adoption could also exacerbate existing shortages and contribute to misalignments between skills and needs in the labour market, including pre-existing needs for upskilling the labour force (Ryan, 2023).

The labour force for atypical protein production will draw on a different pool than other production methods

Labour shortages and skills mismatches identified in the agri-food sector are not immediately pertinent to cellular agriculture, for example, which may draw on a different labour pool than conventional farm work (Bock *et al.*, 2020;

Ontario Genomics, 2021). The labour outlook for novel protein production may be less dire since it draws on competencies in engineering biology, food technology, and other disciplines in which Canada has expertise (Ontario Genomics, 2021). The need for highly skilled labour, however, comes at a cost. For example, Humbird (2021) takes the salary of a chemical plant operator to benchmark labour costs in cellular agriculture. Cellular agriculture operators may be competing with the health and industrial biotechnology sectors for labour, with implications for operating costs and business models (Ontario Genomics, 2021).

Labour in CEA facilities is the largest operational cost, though it may be reduced through automation

Labour expenditures in CEA facilities are generally the highest operational expenses, followed by energy costs (Agritecture Consulting & Autogrow, 2019; Nicholson *et al.*, 2023). The exact range varies; in 2022, Canadian greenhouse operators spent 28% of their total operating expenses on gross annual payroll for both seasonal and permanent labour (StatCan, 2024d). Other estimates indicate that labour made up over 70% of the grow-cost per pound of produce in a greenhouse and a vertical farm (Tasgal, 2019). Regardless, improving the productivity of labour in CEA facilities is necessary if costs are to be reduced to a level comparable to field-based agriculture; this may be addressed through automation of various processes (Nicholson *et al.*, 2020, 2023). Nicholson *et al.* (2023) found that:

> *automated systems (whether urban or peri-urban) generally have lower overall landed costs due to much lower labour costs, despite higher costs for the initial investment in structures and equipment. The most cost competitive [greenhouses] are automated peri-urban systems, which have lower labour costs (from both automation and location) that more than offset higher investment and transportation costs.*

A comprehensive approach for skills development would support the modernization of the agri-food sector

Technology and automation are acting to displace and reallocate labour while spurring changing demands for skills, with implications for atypical production methods that follow technological innovations. The World Economic Forum projects that agricultural equipment operators will represent the fastest-growing job role over the coming five years (WEF, 2023). Despite calls for a comprehensive agriculture skills national strategy (Phillips, 2023), evidence gaps in the agri-food labour market defy efforts to operationalize coherent skills development policies (AAFC, 2023c; Ryan, 2023). The skills deficit is furthered by Canada's uncoordinated approach in funding agri-food R&D, and commercialization issues (AIC, 2017b).

In the agricultural sector, the workforce must develop a wide range of skills. These include hard skills, such as those relating to agronomy or financial decision-making, and soft skills, in particular those that enable adaptability and a disposition toward lifelong learning (CRETAU, 2020; Ryan, 2023). High-tech skills, such as specialized skills in genomics (both from technical and regulatory standpoints) and skills relating to data and information technology are also increasingly in demand for agriculture generally and CEA specifically (Stackhouse *et al.*, 2019) (Section 4.2). Amidst these shifting skillsets, the term farmer takes on new meanings, and this reality is reinforced when considering advances in technologies for atypical protein production (Bock *et al.*, 2020). Cellular agriculture, for example, requires not only a novel skillset, but work activities and environments that differ some those of livestock farming (Räty *et al.*, 2023).

Beyond technical or digital skills, the labour force may require competencies in integrated systems management, finance, and human resources,[23] as well as communication skills for engaging with consumers (Bock *et al.*, 2020; CAHRC, 2023). An EU study on the future of farming also highlighted that key skills needed for CEA and alternative protein production include entrepreneurial capacities, and the ability to identify new biotechnologies for integration into existing operations; for producers of alternative proteins, the study also emphasized a requirement for food technology training (Bock *et al.*, 2020). A training resource published by Ohio State University provides an overview of the broad range of technical and business-related capacities required for CEA operators, including a list of more than twenty disparate skills ranging from plumbing and basic construction to computer science and strategic planning (Albert *et al.*, 2019).

"Amidst these shifting skillsets, the term farmer takes on new meanings, and this reality is reinforced when considering advances in technologies for atypical protein production (Bock *et al.*, 2020).

Several avenues exist to meet the labour needs articulated above, including formal or on-the-job training (e.g., Cornell, n.d.) and hiring skilled labour from non-agricultural labour pools (Yaghi, 2023). Nearly half of farm operators under the age of 35 possess post-secondary (including CEGEP) education,

23 Effective management is perceived as a contributor to employee retention (CAHRC, 2023).

and enrollment in post-secondary agriculture programs is growing (StatCan, 2024e), suggesting that the workforce is enthusiastic to develop the above skills through education. However, training modalities, particularly in remote areas, must reflect the existence of geographical barriers to participation: farmers tend to be active participants in lifelong learning, but the physical requirement of being on-farm complicates involvement in education and training (Räty *et al*., 2023).

5.3 Conclusion

Implementation of atypical food production technologies and facilities relies on an enabling environment that provides adequate resources and supports to Canadian producers. Energy, water, internet access, and considerations for logistics and transportation are all vital to the operation of facilities, and ensuring adequate economic conditions and labour is an ongoing concern. Alternative financial tools and approaches may improve the economic sustainability of CEA operations, particularly if the associated technologies realize their promise of low environmental impacts. Labour remains a challenge in agriculture more broadly but is also particular to CEA due to the specialized nature of many jobs requiring unique training.

The supports and resources discussed in this chapter are requirements for implementing the technologies described in Chapters 2 and 3 and act as supplements to the enabling technologies comprising Chapter 4. Creating the enabling conditions to support atypical food production technologies further relies on regulations and policies (Chapter 6).

6

Policy and Regulatory Landscape

Chapter findings

- Food production is under shared jurisdictional authority, with a governance landscape shaped by field-based agriculture.
- Several aspects of land-use regulation can hinder the establishment of atypical food production, restricting the location and constraining the properties of production facilities.
- Obtaining approval for some atypical protein products may challenge existing regulatory mechanisms due to a lack of comparator products for assessing food safety risks.
- Empowering local project leadership increases the chance of success for atypical food production operations by ensuring projects are mindful of local infrastructure and labour contexts, and aligned with community needs and desires.

The production and sale of food in Canada is governed through an extensive system of legislative and policy instruments subject to oversight from federal and provincial or territorial departments and agencies, municipal governments, and Indigenous governments (GC, 1982; Berger Richardson & Lambek, 2018). Food production requires land, labour, and physical infrastructure, each of which are, to varying extents, subject to regulatory oversight. Regulations may also facilitate or hinder the provision of many types of resources (e.g., water, fertilizer, funding) needed to establish or maintain operations. Through the rules and policies they enact, all orders of government have an impact on whether conditions are favourable for atypical food production.

The exact policy and regulatory considerations for atypical food production vary across the numerous permutations of production typologies and locations, and a comprehensive investigation of these is beyond the panel's remit. Instead, this chapter considers two essential areas of regulatory oversight presenting complex but distinct challenges. First is an examination of land-use policy, which considers zoning and other barriers faced by CEA operators. The chapter then discusses regulations and policies around food safety and how these might be challenged by atypical production methods. Finally, the panel presents an overview of opportunities and challenges in food system policy-making for atypical production geared toward local consumption, focussing on the coordination of policies and prioritization of community needs.

6.1 Land-use regulation

While CEA operations typically use less land than conventional production, access to sufficient land area is still critical to many operations. Land is managed through land-use planning, which aims to account for socioeconomic and environmental considerations while weighing regional needs against the priorities of property owners (Gov. of ON, 2023a).

Complexity in the jurisdictional authority over land-use regulations can be a barrier to establishing atypical food production

The division of authority over land-use planning varies across the country. Most commonly, it rests with provinces and territories, but there are also lands controlled or owned by the federal government (GC, 1982; Becklumb, 2013), and others under the authority of Indigenous governments (see, for example, Gov. of NT, n.d.). Regardless of authority, the regulatory implementation of planning for land is often delegated to local orders of government. For example, provincial or territorial authorities might use regional plans to define broad policy objectives or guidelines, which are subsequently put into practice through municipal bylaws or other instruments according to specific rules (OECD, 2017). In other cases, land-use regulation is carried out through environmental legislation, either to enable agricultural land uses (e.g., Ontario's Greenbelt) or prevent such uses on the grounds of environmental protection (e.g., water contamination) (e.g., OFA, 2021; Gov. of ON, 2023b). There are also specific agricultural land-use issues in the North pertaining to the potential role played by certain lands in climate-regulation services and biodiversity (Meyfroidt, 2021).

Some First Nations reserve lands fall under federal jurisdiction as dictated through provisions in the *Indian Act* (GC, 1985), but several efforts are underway to restore governance authority to Indigenous communities through initiatives such as the Reserve Lands and Environment Management Program, and legislation including the *Framework Agreement on First Nation Land Management Act* (GC, 2014a, 2022). Signatory communities are provided with guidance and resources for establishing land codes and developing land-use plans, such that the management of lands, the environment, and natural resources can proceed according to community-developed rules that are consistent with First Nations legal frameworks (LABRC, 2019; GC, 2022). Over 200 First Nations communities are at various stages of implementing the *Framework Agreement* (LABRC, 2024). In addition to issues surrounding the social acceptability of technologies for atypical food production (Section 5.2), challenges relating to the regulation of land may vary according to individual communities on the basis of their specific land codes.

The multi-jurisdictional nature of land-use governance means policies and regulations related to food production may exist across several orders of government, and these are not strictly harmonized (Berger Richardson & Lambek, 2018). Planning aims to separate incompatible land uses, and agricultural production has been deemed incompatible with numerous other forms of land use (e.g., residential development) that limit where facilities can be located. Furthermore, the planning criteria used to determine the "best" use of land are not developed with agriculture in mind (Thibert, 2012). The inconsistent accounting for food systems in planning may complicate processes for identifying and obtaining approval for sites dedicated to atypical food production.

Zoning dictates where atypical food production facilities are permitted, and raises barriers to establishing facilities in desirable areas

The planning process typically culminates in zoning rules, which delineate acceptable types of development on a given parcel of land. In Ontario, for example, the scope of zoning bylaws includes the definition of how land is used, the types of permitted structures (and their location on the land), and several additional parameters, such as maximum building heights (Gov. of ON, 2019). Zoning also sets requirements relating to water supply and waste management. While it is possible to apply to obtain exceptions from zoning requirements through minor variances or bylaw amendments, such applications typically involve a deliberative process among developers, government representatives, and community members, which can add cost and delays in establishing growing operations (e.g., Valdez, 2017; Kanally, 2023).

Zoning laws were not designed with novel food technologies in mind. The high-tech nature and specific land-use requirements for CEA facilities can make them difficult to classify in current zoning rules (Lubna *et al.*, 2022). CEA facilities may include (or be built inside) structures regulated under zoning categories that are typically distinct (Thibert, 2012; Mackey, 2016), and zoning rules may even prohibit the on-site sale of produce (Huang & Drescher, 2015). Incompatibility with typical zoning rules creates barriers for CEA applications, even in cases where land is explicitly zoned for agriculture through provincial programs and legislation.

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Incompatibility with typical zoning rules creates barriers for CEA applications, even in cases where land is explicitly zoned for agriculture through provincial programs and legislation.

One example is B.C.'s Agricultural Land Reserve (ALR) and the accompanying *Agricultural Land Commission Act*, which were created as a means to use zoning to support agriculture by preventing agricultural land from being developed for urban expansion (Runka, 2006; Gov. of BC, 2024). Although the ALR protects agricultural land and supports the food system, it does not necessarily act to support atypical food production. It is a farmland reserve program, and urban areas are not typically part of ALR holdings. This policy would not benefit, for example, vertical farming applications for local production in dense urban environments (Soderholm, 2015). In 2022, changes were made to ALR regulations to explicitly permit vertical farming applications on ALR land (Gov. of BC, 2022). However, ALR regulations do not replace municipal or local bylaws, some of which have prevented vertical farm developers from securing appropriate land despite the overarching regulatory changes (Hui, 2023). *The Future of B.C.'s Food System* report outlines how the above-listed tensions might be relaxed through amendments to ALR regulations to provide entry points for novel food production technologies (B.C. Food Security Task Force, 2020). In response, others have urged caution and raised concerns that expansion of indoor growing on ALR lands risks threatening soil-based agriculture by increasing competition for, and reducing inventory of, scarce arable land in the province (Hansen *et al.*, 2020).

Some jurisdictions have pursued initiatives to adjust zoning to support CEA

Some governments have adjusted zoning rules to enable CEA in regions where it was previously prohibited. Changes include modifications to lists of permitted activities, amending bylaws to account for changing technologies, and allowing the sale of urban produce (reviewed in Mackey, 2016). Planning policies in some EU countries also provide specific rules to assist in integrating CEA into structures, both privately and publicly owned (Marini *et al.*, 2023), to overcome the issue of building codes lacking provisions for indoor crop production at scale (Simpson, 2019). The 2020 *National Building Code of Canada* includes updated provisions for farm buildings of various types, including greenhouses and other indoor facilities for growing plants (CCBFC & NRC, 2020), allowing some CEA technology vendors to market code-compliant solutions (Growcer, n.d.).

Resolving zoning issues or ambiguities requires consideration of local contexts since zoning constraints typically reflect the cumulative result of past planning decisions (Simpson, 2019; Schindler & Dionisio, 2021). According to a review of planning in several municipalities, planning authorities in Canada have taken additional steps to account for food systems to an extent that is growing but variable in implementation (OPPI, 2011; Huang & Drescher, 2015; Soderholm, 2015). The integration of food systems into land-use planning requires overcoming several challenges, including: such as identifying and consulting with affected parties at regional levels; meeting the distinct needs of urban and rural communities; incorporating food systems across planning policies; and propagating these policies across several operational dimensions from official plans to secondary plans to zoning bylaws (OPPI, 2011).

In some cases, targeting peri-urban development through appropriate land-use policy tools may enable atypical producers to establish operations that have proximity to urban centres without being located in dense urban cores. A 2020 review found that CEA operations integrated into existing built structures are most commonly found in peri-urban settings (CRETAU, 2020).[24] These settings provide an alternative to costly urban or agricultural land while allowing access to water (FAO, 2022; FCC, 2023b), and could also promote access to energy and labour due to the proximity to dense urban areas.

6.2 Food safety regulation

Before a new food can be sold in Canada, Canadian regulators assess its safety and may oversee several additional dimensions of its production, including inputs and processes. The oversight of agriculture and domestically produced food in Canada is accomplished through several pieces of legislation and accompanying regulations, the most relevant of which are presented in Table 6.1. In addition to providing regulatory oversight, federal agencies can also be responsible for additional policy measures, including standards and guidelines (CFIA, 2020). Some of these measures are directly relevant to atypical production, such as the standards for organic production in the context of CEA (GC & CGSB, 2021), while regulatory clarity may still be lacking for other emerging atypical products.

Table 6.1 Selected legislative components of the Canadian federal regulatory landscape for food production and safety

Agency	Product(s)	Act(s)	Regulations
Canadian Food Inspection Agency (CFIA)	• Seeds • Plants with novel traits (PNTs) • Food that is imported, exported, or shipped interprovincially	• *Seeds Act* • *Plant Protection Act* • *Safe Food for Canadians Act*	• *Seeds Regulations* • *Plant Protection Regulations* • *Safe Food for Canadians Regulations*

(continues)

24 Container CEA facilities tend to be concentrated in small municipalities or major urban centres (CRETAU, 2020).

(continued)

Agency	Product(s)	Act(s)	Regulations
Health Canada	• Health and safety of all foods	• *Food and Drugs Act*	• *Food and Drugs Regulations*
Fisheries and Oceans Canada (DFO)	• Aquaculture products of biotechnology	• *Canadian Environmental Protection Act, 1999*[25]	• *New Substances Notification Regulations* (Organisms)
Environment and Climate Change Canada (ECCC)	• Biotechnology products not covered under other federal legislation (environmental or indirect human health impacts)	• *Canadian Environmental Protection Act, 1999*	• *New Substances Notification Regulations* (Organisms)

Data sources: CFIA (2016, 2018); HC (2021)

In some cases, novel proteins produced using atypical production may challenge standard regulatory processes for food safety

Before novel foods are sold in Canada, manufacturers and importers must submit evidence to Health Canada to support the safety of these foods (HC, 2021). Data requirements for safety assessment span several categories with potential relevance to atypical food production, such as details regarding novel production processes, the history of the organism used for production, and whether it has been genetically modified (HC, 2021).[26]

To better support its activities in setting policies and standards for food safety in Canada (GC, 2020d), Health Canada conducts food-related health risk assessments to quantify potential health risks to consumers arising from the presence of substances or microorganisms in food (HC, 2008). For atypical protein, the following food safety issues, among others, could be scrutinized as part of the assessment:

- "the safety of the starting cells, particularly from novel sources or those that have been genetically engineered,
- contamination during the growth phases of cell and [precision fermentation] proteins, including the growth broth for cell-based meat,
- potential contamination of the fermentation tank,
- waste disposal, and
- safe handling of products after production."

(Williams, 2021)

25 The statutory responsibility of enforcing the *Canadian Environmental Protection Act*, 1999 falls to ECCC; however, through a memorandum of understanding, DFO administers oversight of these products.

26 Nutritional, toxicological, allergenicity, chemical, and microbiological considerations may also be subject to assessment for foods produced by atypical means.

The risks relating to the above issues are not necessarily novel; however, it may be challenging for evaluators to determine relative risk with respect to substitute proteins (conventional or alternative). The risks associated with novel proteins may differ from the widely understood and studied food safety issues for conventionally-produced proteins (i.e., diseases and pathogens) and may instead come with risks that are comparatively underexamined, such as allergenicity (Fernandez *et al*., 2020a). Recent examples for cultured meat suggest that it may take upwards of a year for regulators and producers to establish and collect the necessary information needed to proceed with market approval (U.S. FDA, 2022; Mridul, 2024).

Guidance issued on the interpretation of regulation for gene-edited plants may facilitate the oversight of novel plants within the existing regulatory framework

PNTs that are intended for use in the natural environment must be assessed by CFIA (CFIA, 2023a). For a plant to be considered a PNT, it must meet the following criteria: "the trait is new to cultivated populations of the species in Canada;" and, "the plant has a potential to have a significant negative environmental effect" (CFIA, 2023b). Gene-editing technologies promise to allow for the production of a wide variety of new cultivars through the ability to impart traits resulting from targeted changes to plant genomes, and some but not all may be regulated as PNTs (CFIA, 2023a). Gene-edited plants will not be subject to regulatory scrutiny by default, with the CFIA (2023a) stating:

> *… there is no inherent risk associated with gene-edited plants that would justify a pre-market safety assessment for the environmental release of seed of every product developed using gene editing. Gene editing technologies do not present any unique or specifically identifiable environmental or human health concerns relative to other techniques of plant breeding. Gene editing can be used to accomplish genetically identical outcomes to what would be achievable using conventional breeding practices. Therefore, gene-edited plant products should be regulated like all other products of plant breeding.*

This guidance aligns with views widely held by major scientific academies and international organizations (Qaim, 2020). Several criteria related to novelty will nevertheless trigger regulatory oversight for gene-edited plants, such as issues relating to weediness, herbicide tolerance, or impacts on biodiversity (CFIA, 2023a). Moreover, since these will be intended for sale as novel foods in Canada, they will also be screened by Health Canada (HC, 2023b). Although CEA operations would be unlikely to make use of gene-edited plants with herbicide resistance, other agronomically relevant traits (e.g., rapid cycling, reduced plant size; Table 4.2) could fall within the scope of the PNT framework, and could require regulatory oversight prior to market approval (Kwon *et al.*, 2020).

6.3 Policy directions

There are a range of instruments—including policies and incentives—that can be instituted to encourage the development of atypical food production (Table 6.2). Several factors must be examined when considering which approaches are most effective and appropriate for a given technology and context, including the existing policy environment, potential trade-offs, and community needs.

Table 6.2 A range of policy tools exist for supporting CEA and other forms of novel agricultural production

Category of policy instrument	Area of action	Example
Legal and regulatory	• Land-use planning and urban planning • Regulatory concessions	• Zoning changes • Permitting on-site sales
Economic incentive	• Grants • Subsidies or reduced taxes • Incentives for technology implementation	• Support through competitive grants • Reduction of property taxes
Voluntary incentive	• Institutional support • Educational activities • Provision of land	• Creation and operation of grower associations • Collaboration with educational institutions • Direct provision of public land for atypical production

Adapted from Marini *et al.* (2023)

Several policy levers may support CEA development, but care must be taken to ensure effective coordination and avoid conflict

In practice, trade-offs may arise within each of all of the categories listed in Table 6.2. In the case of land-use planning in B.C.'s ALR, for example, the intention to lower barriers for vertical farming was shown to raise tensions between local and regional decision-making bodies, and between technology developers and conventional growers (Hui, 2023). On a broader scale, fragmentation within and between orders of government exacerbates these and other challenges, since effective food policies call for a systems approach accounting for competing jurisdictions and geographic coverage (Berger Richardson & Lambek, 2018).

Policies to support local food production often do so under the umbrella of broader cross-cutting policy objectives—for instance, support for environmental protection, enhanced well-being, and strengthened local economies—but even in well-resourced North American cities, such policies often do not translate to comprehensive strategic plans for implementation (Schreiber *et al.*, 2023). It is also important to understand how multiple policies interact within efforts to promote local food production. For example, policies that might support reliance on imported goods through predefined supply systems or other subsidies might challenge the ability of a local producer to become established or to achieve economies of scale through growth (Blom *et al.*, 2022). Even in locations where there is a will to engage in novel agricultural development, pre-existing agreements (e.g., subsidies for large-scale grocers to bring food to the North) may prevent local producers from being able to compete (Blom *et al.*, 2022). For example, Nutrition North Canada deploys multiple economic and voluntary incentives as described in Table 6.2 (GC, 2014b). If a participating community expresses a desire to pursue CEA, it would be essential to determine the interplay between Nutrition North Canada programming and potential new policy initiatives. In all cases, the local context will dictate whether it is more appropriate to support adoption directly, or whether it is sufficient to simply reduce barriers (Wilkinson *et al.*, 2021).

Awareness and support of community needs can inform effective policy-making while promoting public acceptance and building local capacity

Policy-making for food production is decentralized; however, bottom-up, community-led processes can act as effective drivers to create policies for local agricultural initiatives and to address implementation gaps (Huang & Drescher, 2015; Pereira *et al.*, 2024). Frameworks exist to ensure that local priorities are embedded in the design of food policies and revisited throughout the policy life cycle (Figure 6.1). Engagement is essential to advance and progress policies along the cycle. The framework may not be practical for some aspects of atypical food governance, such as federal food safety regulations, but it can be effective for considering activities such as those described in Table 6.2, where local considerations are most pronounced. Although the cycle in Figure 6.1 focusses on urban agriculture, the salient features apply to other

> Another strategy for ensuring the continued success of CEA facilities may be to ensure local community members operate agricultural projects by providing training and decision-making influence over what types of food are prioritized.

locations considered unconventional for agricultural activities and allow communities to participate in aspects of the food policy-making process directly.

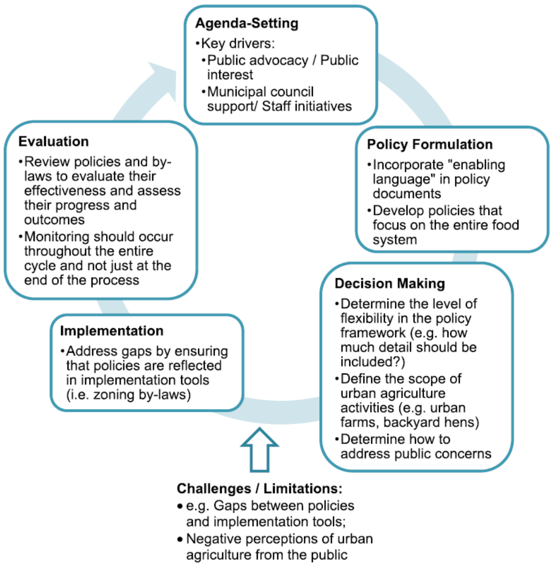

Figure 6.1 Life cycle for engagement-oriented design and implementation of agriculture policies

There are opportunities to use policy to support agriculture in unconventional areas. However, the design and implementation of policies should consider the wider context, including the challenges being tackled as well as community needs and preferences. Ensuring policies are evaluated on an ongoing basis helps to identify outcomes, gaps, and areas for improvement.

For example, if community members are struggling to locate suitable land for production, local governments can initiate dialogues about planning by investing in food system asset maps (Huang & Drescher, 2015). Another strategy for ensuring the continued success of CEA facilities may be to ensure local community members operate agricultural projects by providing training and decision-making influence over what types of food are prioritized, as has been practised by the community-run hydroponic facility in Gjoa Haven, Nunavut (The Canadian Press, 2020).

Community buy-in may additionally be increased through a local project champion. Project champions are often community members who spearhead the introduction of new technologies or concepts, and who can leverage existing credibility within the community to get projects off the ground (Seguin *et al.*, 2021). Demonstration projects can be useful ways to allow project champions to see CEA technologies in person before taking on projects in the communities (Box 6.1). However, the burden of maintaining operations and outreach can then fall to a single person, increasing the risk of burnout and subsequent failure of agricultural projects (Seguin *et al.*, 2021). An additional avenue for encouraging community uptake and buy-in involves building off of, or providing support for, existing initiatives such as greenhouses (Wilkinson *et al.*, 2021). In the North, agricultural centres such as the Tr'ondëk Hwëch'in Teaching and Working Farm (Yukon) and the Inuvik Community Greenhouse at the Gamètì Community Garden (Northwest Territories) offer opportunities for collaboration and knowledge gathering (Seguin *et al.*, 2021). Based on panel experience, participation by Elders or Indigenous knowledge keepers who can provide guidance and support to project champions may also be critical for the success of CEA in Indigenous communities.

Box 6.1 Innovation hubs and demonstration projects

One avenue for introducing CEA in target regions involves using innovation hubs to bring together agricultural specialists and those interested in starting their own ventures. Innovation hubs have been suggested for use in the North to overcome learning barriers and facilitate knowledge exchange among communities (Hintsala *et al.*, 2017; Blom *et al.*, 2022). Associations and non-profit or non-governmental organizations play an important liaison role while also potentially helping to navigate policy and regulatory landscapes (Marini *et al.*, 2023). An innovation hub model can also be an opportunity for trialling; one barrier to the uptake of technologies with a high initial investment cost is a lack of surety in their projected outcomes (Hintsala *et al.*, 2017). To alleviate user concerns, communities or potential champions could be supported in trialling technologies, visiting locations where these technologies are already established, and using such visits as opportunities to learn, train, and assuage fears (Natcher *et al.*, 2021). Promoting innovation hubs and cross-community communication is difficult, however, especially in regions that have limited transportation infrastructure like the North (Natcher *et al.*, 2021).

Community-led development is important for ensuring the success of CEA in Indigenous communities

Ensuring programs and initiatives related to Indigenous food sovereignty are driven by the needs and priorities identified by Indigenous Peoples themselves is essential for success (Loring & Gerlach, 2015). This can involve the application of CEA principles toward culturally valuable species, which may support greater resiliency to the changing climate. In the experience of members of the panel, there may be interest in domesticating species for growth inside CEA, with one community in Cambridge Bay, Nunavut, identifying upwards of fifteen small fruits and edible species from the tundra for potential cultivation. Nevertheless, the panel notes that many species remain challenging to grow in CEA (e.g., cloudberries), with further research required to determine optimal growing conditions. In some situations, agriculture is identified as a way for communities to support their own food sovereignty (Price *et al.*, 2022). In cases where CEA is seen as desirable by the community, it could take place alongside other solutions that contribute to local food production and food security, such as community gardens, school gardens, co-operatives, and traditional food initiatives (Sumner *et al.*, 2019). A review of local food initiatives in Indigenous communities by Sumner *et al.* (2019) found that community gardens and greenhouses are the most common types of social-economy initiatives, specifically targeting local issues. These findings are exemplified in the community gardens of several communities in the Northwest Territories (Ka'a'gee Tu First Nation and Sambaa K'e First Nation), where "no matter who tends the gardens, the entire community shares the harvest" (Price *et al.*, 2022).

In some cases, alternative forms of markets, including social economies and co-operatives where community needs are prioritized, may be more suited to Indigenous food systems than conventional, capitalist markets (Wuttunee, 2010 as cited in Sumner *et al.*, 2019). Moving away from profit-based models can support local food production; Sumner *et al.* (2019) found that the support from non-profits in Manitoba led to a high concentration of local food initiatives, including those related to procurement, financing, technical support, education and training, and opportunities for knowledge exchange and collaboration (Box 6.2).

> A given policy (or technology) will not be successful in achieving its goals if it is developed in isolation from the community where it will be applied.

Box 6.2 Northern Manitoba Food, Culture, and Community Collaborative (NMFCCC)

Through partnership with a number of public and private funders, the NMFCCC provides grants ranging in value from $1,000 to $30,000 per project to eligible Indigenous communities in northern Manitoba (NMFCCC, n.d.-a,-b). This funding is targeted at supporting community-led projects for "strengthening food systems, culture, wellness, education opportunities and local economies" (NMFCCC, n.d.-c). To date, the NMFCCC has fostered partnerships with many local food initiatives to develop projects concerning on-the-land learning, beekeeping, cooking, wild food processing, and community greenhouse projects (NMFCCC, 2021).

6.4 Conclusion

The interaction between the regulatory environment and atypical food production systems can raise several challenges due to the potential novelty of the associated products and processes, as well as the locations for production that are, in comparison to typical modes of agricultural production, unconventional. Policy approaches to enable atypical food production need to resolve numerous tensions to establish a common language among a broad set of interested parties and decision-making bodies. Tensions around the implementation of regulations and policies related to land use and food safety, for example, will need to be resolved to address the differences between atypical and conventional food production. There are also opportunities to use policy to enable and encourage growth in atypical production (e.g., zoning to support CEA). At the same time, coordination across the policy landscape (including among orders of government) is needed to ensure new initiatives meet their goals and do not create new barriers or have unintended consequences in local food systems. In complex cases where existing policies and programming already intersect, decision-makers should assess the appropriateness of new policies, and how existing policies might be adjusted.

The regulatory and policy environment is complex, and food lacks a policy home. Several opportunities also exist for participatory governance; however, food policies should reflect local priorities, for example, in land-use planning or program design for local incentives. Moreover, though considering community needs and goals is important for all policy development, it is essential for Indigenous communities. A given policy (or technology) will not be successful in achieving its goals if it is developed in isolation from the community where it will be applied.

7

Conclusion: Linking to Food Security

Chapter findings

- Advances and innovation in atypical food production technologies will affect only a small portion of the greater food system. Furthermore, these technologies will not address the root causes of food insecurity in Canada.
- No single technology or type of production facility meaningfully addresses each component of food security on national, regional, or local levels simultaneously.
- On a community scale, CEA has the potential to support greater availability of produce while also enabling agency in cases where projects are desired by the community.
- CEA could support greater resiliency and stability in the food system in the face of future disruptions and shocks.
- The expansion of atypical protein production offers an opportunity for Canada to strengthen its leadership in protein production while promoting greater resiliency by diversifying the food system.
- Innovations and advancements in atypical food production technologies are subject to social, economic, and resource-related trade-offs, which must be considered alongside any potential benefits.

The technologies examined in this report may have the potential to contribute to the six components of food security (Figure 7.1), albeit in a narrow way. Recalling Figure 1.1, production is only a small slice of the broader food system, and the technological advances discussed in this report only pertain to a small portion of production itself. Thus, the panel emphasizes that although there may be some gains for food security in advancing and innovating these technologies, they are not a panacea and will not address the root causes of food insecurity in Canada. In addition to the technologies themselves, several enabling conditions are necessary to achieve their full potential.

> The panel emphasizes that although there may be some gains for food security in advancing and innovating these technologies, they are not a panacea and will not address the root causes of food insecurity in Canada.

In this chapter, the panel identifies the atypical food technologies discussed in previous chapters that may address aspects of food security, as well as the enabling and supporting conditions required for their success. First, the panel considers CEA and then examines atypical protein production. Overall, the panel finds that the greatest potential for advancements in atypical food production technologies to affect food security is through diversification of food sources (affecting stability and agency) and improved sustainability (primarily in the environmental and economic domains).

Data sources: Ericksen (2008); HLPE (2020)

Figure 7.1 The six components of food security

Food security has multiple related but distinct components operating at a range of scales: the availability of food nationally, household food accessibility, and individual utilization of food. Agency, stability, and sustainability are overarching dimensions affecting the other three.

7.1 Food security and CEA

7.1.1 Accessibility

Accessibility concerns *affordability* ("the purchasing power of households or communities relative to the price of food; the cost associated with harvesting, hunting, and fishing of local, traditional, and/or country foods"), *allocation* ("the economic, social, and political mechanisms governing when, where, and how food can be accessed by people") and *preference* ("social, religious, and/or cultural norms, values, and practices that influence consumer demand for certain types of food") (Harper *et al.*, 2022; adapted from Ericksen, 2008). In this section, the panel focusses on affordability; Section 7.2 discusses the potential of CEA to increase consumer choice.

CEA technologies will not drastically impact food affordability in Canada

A lack of accessible food is closely linked to the affordability of food and, therefore, to poverty in Canada. Food insecurity is described as a measure of material deprivation; hence, it is most prevalent among households that have inadequate financial resources, unreliable incomes, and limited access to credit (PROOF, n.d.–a). Household food insecurity is closely linked with other social and economic disadvantages, and households that rely on social assistance or employment insurance are most likely to experience food insecurity (Tarasuk *et al.*, 2022). Improving access to food depends on social supports and programs that are out of the scope of this report; however, a significant body of research and related recommendations have been produced (e.g., CCA, 2014; ITK, 2021; Tarasuk *et al.*, 2022; PROOF, n.d.–b).

In the North, where levels of food insecurity are high, "the problem is not that adequate healthy foods are not available, but that people do not enjoy consistent and reliable access to these foods" (Loring & Gerlach, 2015). Critically, emphasis on technological solutions to food challenges has been criticized for shifting focus away from social and economic solutions, which are better suited to addressing social inequalities at the root of food insecurity (Klerkx & Rose, 2020). Although, food insecurity is highest in the territories and is connected to historical and ongoing colonialism in Indigenous communities, the links between food insecurity and social inequality are not unique to the North (PROOF, n.d.–a,–c). For example, academic researchers have criticized *The Future of B.C.'s Food System*, a report released in 2020 (B.C. Food Security Task Force, 2020), for having a scope that inadequately addressed the true causes of food insecurity in B.C., and for indicating that agricultural technologies (including CEA) offer wide-ranging solutions to social issues without meaningful evidence to support these claims (Hansen *et al.*, 2020).

CEA, and indoor farming in particular, have not yet proven to be consistently more affordable to consumers than conventional alternatives (though work relating to location and scale of operations to improve affordability is ongoing); high start-up, operation, and maintenance costs prevent these technologies from contributing to the accessibility of food. Currently, the focus on expensive, leafy greens limits access to those with adequate disposable income to purchase these products (Dsouza *et al*., 2023); high operating and start-up costs, especially in urban areas, require producers to focus on profitability. In the panel's view, high costs to consumers associated with CEA-produced foods highlight the tension between economic and social demands inherent to the food system as it stands.

7.1.2 Availability

Availability refers to aspects of *production* ("amount and types of food available"), *distribution* ("how food is made available, in what form, when, and to whom"), and *exchange* ("how much of the available food is obtained through exchange mechanisms such as food sharing, bartering, trading, purchasing, or loans") (Harper *et al*., 2022; adapted from Ericksen, 2008). Table 7.1 reviews potential links between CEA technologies and food availability.

CEA may increase the availability of fruits and vegetables on a community scale

Food availability[27] (for many major commodities, such as fresh fruit and vegetables, flour, eggs, and meat products) is generally high and stable in Canada (StatCan, 2023d, 2024f). On a local or seasonal level, however, certain types of food may not be readily available due to a range of factors, such as supply chain disruptions or crop failure (Pereira *et al*., 2024). The panel also notes that as these disruptions impact availability, they may also affect the cost or accessibility of certain products, altering CEA's feasibility and attractiveness. This gap in availability is pronounced in communities where the availability of healthy, fresh produce is low (e.g., remote and northern regions) and the risk of supply chain failure is high (Lemay *et al*., 2021). Improving the availability of certain crops may be particularly relevant for supporting food security in communities with localized health issues (e.g., high levels of diabetes). Further, in the experience of one panel member, fresh and readily available produce from a local CEA facility may have greater community uptake when paired with education around the benefits of including certain vegetables for managing diabetes.

27 Food availability is considered as an aggregate, defined as retail weight (not adjusted for losses to, for example, waste or spoilage in stores, households, or institutions) (StatCan, 2023d).

Table 7.1 The potential and requirements of CEA to improve food availability

	Technology	Potential	Requirements
Availability	CEA as a whole	• Increased production of certain fruits and vegetables locally	• Supporting infrastructure in place (water, energy, internet) • Mechanisms for financing new CEA operations • Located in places most reliant on long supply chains • Use of sustainable and renewable resources
	UV transmitting films (ETFE) in covering materials	• Cold climate adaptability	• Financing options to reduce installation costs • Access to materials and requisite training for installation
	Full spectral control of lighting	• Ability to grow multiple crops in the same space (attractive for smaller operations in remote locations)	• Technology that is efficient, low cost, and highly durable • Reliance on LED lighting

Climate change effects have been found to have the greatest impact on Indigenous Peoples and northern regions. For instance, climate change affects the safety and longevity of winter access roads, which can further increase already high food prices by narrowing transportation windows (Rall & LaFortune, 2020). Producing food locally or regionally can reduce dependence on long and vulnerable supply chains, thereby reducing vulnerability to climate change and increasing the availability of certain types of food that are primarily imported (e.g., fruits, vegetables).

7.1.3 Utilization

Utilization (or food use) considers *nutritional value* ("how much of the daily requirements of calories, macronutrients, and micronutrients are provided by the food people consume"), *social value* ("the social, religious, and/or cultural functions and benefits that food provides"), and food safety ("microbial or chemical contamination introduced during producing, processing, packaging, distribution, handling, or marketing food") (Harper *et al.*, 2022; adapted from Ericksen, 2008).[28] The panel emphasizes that emerging technologies related to other parts of the food system (e.g., shortening transportation

28 Some definitions of utilization include food allocation within a household, and "variation in the extent to which the nutrients in food are able to be absorbed and metabolized by individuals within households (e.g., because of differences in health status or the bioavailability of micronutrients)" (Jones *et al.*, 2013). These aspects, however, are not addressed by atypical food production.

times, improving storage potential) can substantially impact food safety and nutritional value; however, these technologies are out of scope for the report. Table 7.2 reviews potential links between CEA technologies (and enabling technologies) and food utilization.

Table 7.2 The potential and requirements of CEA to improve food utilization

	Technology	Potential	Requirements
Utilization	Light spectrum manipulation	• Improve the nutritional value and flavour of certain crops grown in CEA	• Adequately sensitive LED arrays and controls • Sufficient and efficient energy sources to operate
	UV transmitting film in covering materials	• Improve the nutritional value of certain crops grown in CEA	• Sufficient testing and research • Trade-off with biomass and yield; prioritization of social and nutritional benefits
	Microbiome engineering	• Improve the nutritional value of certain crops grown in CEA	• Additional testing and research to replicate lab results in CEA
	Gene editing of plant species	• Improve the nutritional value of foods grown in CEA • Increase the social or cultural value of CEA by allowing certain crops to be grown or started for growth indoors	• Community involvement and leadership, particularly for Indigenous communities • Regulatory clarity to provide a predictable environment for innovation in plant breeding • Additional research to determine if individual nutrition is improved while consuming products as part of a normal diet

Atypical production enables changes in the nutritional value of fruits and vegetables that can target needs and preferences

The combination of CEA and the enabling technology of gene editing (Section 4.1) may improve access to produce that is more nutritious than conventional produce or that targets nutritional deficits in certain populations (Box 4.1) (Hiwasa-Tanase & Ezura, 2016), although further research on impacts is needed. Other technologies within CEA can also affect the nutritional value of certain crops, such as manipulation of light spectra, alteration of nutrient mixes, and temperature adjustment (see Table 2.1). However, despite the ability to enhance the nutritional content of CEA-grown plants, there is a lack of evidence to suggest health improvement in individuals consuming said produce, even in populations with particular nutritional deficits. In the panel's view, affecting the nutrition of individuals may be better served by increasing the availability of healthier options where few currently exist.

Growing culturally valuable plants indoors may improve their resilience if the method is appropriate for a given food system

In the panel's experience, CEA may offer opportunities to address the climate risks faced by native plants, especially high-value crops for Indigenous communities (Section 6.3). Growing certain plants indoors proximal to their natural ranges may help improve access and reduce the risk of food insecurity caused by insufficient harvests. For example, CEA offers the opportunity to propagate seedlings for crops that are slow-rooting or are vulnerable to harsh conditions when young (Gibson *et al.*, 2020). Once sufficiently mature, these plants can then be transplanted outdoors. In the experience of one panel member, this may be an attractive prospect for some communities wishing to use CEA as a starting point for growing high-value crops before transferring them elsewhere (e.g., existing community gardens, personal gardens, community growing projects). Critically, however, these solutions are reliant on community leadership and support. Such leadership is particularly important in the case of Indigenous communities, as the use of indoor growing may not be appropriate for a given food system. The involvement of Indigenous knowledge keepers and community members at the initial stages of planning is an essential component in responsible R&D for the domestication and growth of culturally valued plants using CEA and other associated technologies.

7.1.4 Agency

Agency refers to "individuals or groups having the capacity to act independently to make choices about what they eat, the foods they produce, how that food is produced, processed, and distributed, and to engage in policy processes that shape food systems" (HLPE, 2020). The panel further links agency to Indigenous food sovereignty (Section 1.2). As a reminder, food sovereignty differs from food security by calling for a fundamental shift from viewing food as a commodity to viewing food as a public good, emphasizing its role in strengthening communities, ecosystems, and economies. Table 7.3 reviews potential links between CEA technologies (and enabling technologies) and agency.

Table 7.3 The potential and requirements of CEA to improve food agency

	Technology	Potential	Requirements
Agency	CEA as a whole	• Improved food sovereignty for Indigenous Peoples living in remote locations by providing more options for fresh produce • Local produce for those who value local production	• Desired and led by the community • Supporting infrastructure in place (e.g., water, energy, internet) • Parts available for maintenance and repair • Adequate training and funding opportunities, and labour availability

CEA may support consumer preferences for locally grown produce

Despite not necessarily being more economically or environmentally sustainable than field production, CEA may be preferred by certain consumers if it enables local production, particularly in urban and peri-urban areas (Nishi, 2017). This may also be linked to the desire for pesticide-free or organic produce, with consumers willing to pay a premium for these products (Krasovskaia *et al.*, 2023). Thus, CEA can support the agency of certain consumers; however, as discussed elsewhere, these consumers are unlikely to be food insecure.

In some cases, CEA may support Indigenous food sovereignty, offering an alternative to imported market produce

CEA offers an opportunity for fresh produce to be grown in communities that do not have consistent access to it, especially remote Indigenous communities reliant on imported market foods. Should CEA facilities be able to operate in a way that fulfills the needs of communities, they may then be considered one option among many to improve food sovereignty for Indigenous communities. Several greenhouses are already operating part-time in the North, as well as container and vertical farms integrated into community networks and hubs (e.g., Piché *et al.*, 2020; Wilkinson *et al.*, 2021; Ahmad *et al.*, 2022). Key to the success of CEA systems in remote areas—and especially in Indigenous communities—is local leadership and integration into local food systems (Section 6.3). When driven by local needs and supported by the community, growing foods desired by community members (Section 2.3) or cultivating traditionally harvested plants for greater resilience or seasonal availability (Section 6.3) can advance Indigenous food sovereignty and agency over food systems. Furthermore, CEA could potentially have a role in alternative food system dynamics, which move away from market economics and instead focus on local trade and exchange (Sumner *et al.*, 2019).

However, while CEA can be one aspect of a local food production system, it is not a silver bullet. In the northern context, there is "potential for containerized systems to be part of a diversified and integrated food system that has the capacity to meet local and even regional food and nutritional needs … they can function as complementary systems that are place-based, culturally appropriate, and designed to meet specific community needs as defined by a community" (Wilkinson *et al.*, 2021). Some areas that may benefit the most from alternative food production methods also face the most significant challenges to successful implementation. For instance, access to adequate inputs (building materials, repair materials, substrates, nutrients, and seeds), requisite infrastructure (e.g., clean water, electricity, internet), and specialized labour are lower in northern and remote locations in Canada when compared to urban centres or southern Canada (Chapter 5).

Regionality significantly impacts the appropriateness and feasibility of novel food technologies, even across broad areas such as the North. For example, while there are agricultural activities taking place across the North, there were fewer agricultural initiatives in Nunavut, Nunatsiavut, and Nunavik as compared to the Yukon and the Northwest Territories (Seguin *et al.*, 2021). In the former regions, community efforts may be focussed elsewhere, primarily on reducing health inequity, improving housing access and employment, and supporting traditional food pathways through hunting and harvesting (ITK, 2021; Seguin *et al.*, 2021).

The panel emphasizes that regardless of the adoptability of the food production system or facility, agency is ultimately about ensuring that individuals and communities have the capacity to choose the food security solutions that are most appropriate for them.

7.1.5 Stability

Stability refers to the consistency of all the other food security dimensions in the long term, especially in the face of changing conditions and sudden shocks (Harper *et al.*, 2022; adapted from Ericksen, 2008; HLPE, 2020). The panel also includes the concept of resiliency here, as many aspects of the food system are susceptible to climate-related disasters, pandemics, and other social disruptions. Table 7.4 reviews the potential links between CEA and stability of the food system overall.

Table 7.4 The potential and requirements of CEA to improve food system stability

	Technology	Potential	Requirements
Stability	CEA as a whole	• Year-round, consistent availability of specific produce, independent from weather and certain supply chain interruptions, with a lower risk of contamination	• Supporting infrastructure in place (e.g., water, energy, internet) • Adequate operation during temperature extremes • Access to financing • Access to training to maintain labour needs • Located in places most reliant on vulnerable food supply chains • Access to sustainable resources

CEA may provide a more resilient and stable form of production in the face of some climate-related shocks and disasters

The susceptibility of field-based agriculture to climate risks is significant, including crop loss due to drought, flooding, hail, and forest fires (CCA, 2019). Climate risks are only one of a set of challenges that consumers reliant on supply chains for certain fruit and vegetable products from other countries face, as these supply chains depend on transportation networks that can deteriorate and international borders that can close. If implemented in strategic locations with all of the requisite operating conditions met, CEA offers an alternative to field-based agriculture that may provide more stable availability of certain produce and increased resilience to current and future risks.

The dependence on imported fruit and vegetables makes Canadian produce supplies vulnerable to global factors, demonstrating a lack of resiliency in the system (Section 1.2.2). For example, the onset of the COVID-19 pandemic limited trade flows from the United States to Canada over a three-month period (Chenarides *et al.*, 2021). At the same time, there were shifts in consumer demands, with a relocation of food expenditures toward food retail and an increase in purchasing from grocery stores, as well as increased demand for certain items (e.g., flour) (Weersink *et al.*, 2021). In some cases, a lack of capacity in other parts of the system (e.g., logistics, labour shortages) led to food waste, as products could not reach consumers before spoilage.

However, CEA is not without its own vulnerabilities. The reliance on electricity, especially when not linked to in situ or renewable sources, increases the risk of shutdown from power outages (Section 5.1). Furthermore, supply chain disruptions may also affect the delivery of critical resources to CEA facilities, such as water, nutrient supplies, seeds, and maintenance materials. Though CEA may be more resilient in the face of some hazards brought on by climate change, it is not immune. In the panel's view, geographic diversification of food production and robust and resilient supply chains for inputs and products is an alternative way to address climate risk at a local scale.

7.1.6 Sustainability

Sustainability refers to "food system practices that contribute to long-term regeneration of natural, social and economic systems, ensuring the food needs of the present generations are met without compromising the food needs of future generations" (HLPE, 2020). Although evidence is limited, there is some potential to improve the environmental and economic sustainability of atypical food production technologies to strengthen food system sustainability overall. Table 7.5 reviews potential links between CEA (and enabling technologies) and sustainability, relative to commonly deployed technologies (see Table A.1 in the Appendix for examples).

Table 7.5 The potential and requirements of CEA and enabling technologies to improve food system sustainability

	Technology	Potential	Requirements
Environmental sustainability	Spectral manipulation technologies	• Improved energy use efficiency	• Further research to improve stability and fabricability, and to reduce manufacturing costs
	LED lighting	• Reduced energy requirements, greater energy use efficiency	• Continued reduction of production and installation costs
	End of production light treatment	• Reduced food waste through improved shelf life	• Further research and testing into the efficacy and magnitude of the effect
	Continuous lighting	• Increased energy efficiency and reduced costs	• Adequate blocking of nighttime light pollution • Use of renewable energy sources
	Ion monitoring and filtering technologies (ion selective electrode; ion exchange membrane)	• More efficient and controlled recirculation, improved circularity	• Further research to address ambiguous results • Reduction of production and installation costs

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	Technology	Potential	Requirements
Environmental sustainability	Non-thermal plasma for producing nitrogen	• On-demand source of nitrogen	• Further research to move beyond proof of concept
	Novel CO_2 technologies (see Table 2.4)	• Increased circularity and reduced emissions	• Planning and incentives for integration with CO_2-producing industries • Further research into appropriate materials
	Novel technologies for in situ power generation (see Table 2.5)	• In situ energy production to provide requisite energy for HVAC and lighting systems; circularity (using waste to produce energy)	• Efficient, low cost, and highly durable technology • Components made of easily obtainable or renewable materials • Application in environmentally appropriate locations
Economic sustainability	LED lighting	• Reduced energy requirements, greater energy efficiency	• Continued reduction of production and installation costs
	Light spectrum modulation of red/far-red ratio	• Increased yield for certain crops	• Adequately sensitive LED arrays and controls • Sufficient and efficient energy sources to operate
	Disinfection technologies (potassium hypochlorite; non-thermal plasma)	• Reduced loss of crops to disease	• Further research to move beyond proof of concept • Components made of easily obtainable or renewable materials
	Microbiome engineering	• Improved productivity and crop yield • Reduced reliance on fertilizers	• Additional testing and research to replicate lab results in CEA
	Sensors and automation	• Optimization of facility operation (e.g., energy, water, nutrients) • Higher yields	• Robust, adaptable, and affordable devices • Access to data infrastructure • Accessible and reliable AI models
	Robotics	• Reduced reliance on labour to perform certain tasks	• Sensors and controls for data collection • Easily maintained and repaired with readily available materials • A business case to justify the related investments

Reducing reliance on large inputs of energy is key to the environmental sustainability of CEA

Although some aspects of CEA may be more environmentally sustainable than field-based agriculture (e.g., water inputs in some cases; Chapter 2), they nonetheless face a significant challenge: their reliance on energy to operate artificial lights and HVAC systems. Similarly, the energy required for extracting and manufacturing building materials for CEA is substantial, as is the energy requirement for running most systems in mid- and high-tech CEA facilities. For CEA to be environmentally sustainable, a transition to renewable or green energy sources is critical (Chapter 5). This is particularly salient for off-grid locations largely reliant on fossil fuel energy sources prevalent throughout the North.

Further testing and research are needed to substantiate and quantify the claims of increased environmental sustainability of CEA

A review of urban agriculture practices, including rooftop greenhouses and vertical farms, by Parkes *et al*. (2022) investigated the sustainability claims made by producers regarding energy, water, and pesticide use. They found that most producers did not provide adequate data regarding these inputs, so their claims were largely unsubstantiated.

Furthermore, high operating costs and an inability to grow staple crops mean vertical farming has not demonstrably displaced much food production away from arable land, despite offering a yield per area that is higher than that of field-based agriculture and greenhouses (Bomford, 2023). In the panel's view, further research, real-world testing, and reporting are required to confirm any claims of improved environmental sustainability for CEA facilities.

> In the panel's view, further research, real-world testing, and reporting are required to confirm any claims of improved environmental sustainability for CEA facilities.

There are opportunities to use new technologies to increase the economic sustainability of CEA operations

One of the greatest challenges for CEA is maintaining profitability (economic sustainability) to allow for continued operation. CEA facilities have high start-up costs and spend the majority of their operational costs on labour and energy requirements (Sections 2.1, 5.1, 5.2). The greatest potential for improving the economic sustainability of CEA lies with opportunities to improve the efficiency of facility systems (such as lighting or HVAC) to use less energy (and other inputs) per kilogram of produce, as well as increasing the adoption of certain digital technologies to reduce labour costs. Reducing human labour, however, can have negative implications for the livelihoods of those relying on employment in the agriculture industry (Section 5.2). Furthermore, digital technologies face barriers to adoption and security requirements. However, the panel highlights the potential for innovation within CEA technologies to contribute to the expansion of Canada's economy and agri-food sector, as well as the prospect of attracting new entrants possessing high-tech skills to the sector.

7.2 Food security and atypical protein production

As discussed in Chapter 3, atypical protein production technologies show little promise to directly address food security issues in Canada, partly due to high levels of conventional protein production and consumption across the country, as well as consumer preferences for familiar products. Additionally, the importance of country foods for Indigenous communities limits the food security benefit of atypical protein production technologies (apart from seaweed harvest for certain communities) (see Box 3.1). To date, atypical protein generally comes at a higher cost than conventional alternatives, preventing these technologies from contributing to food accessibility. In addition, the lack of commercial production for some of these technologies (e.g., cultured meat) prevents any meaningful assessment of their sustainability.

Instead, atypical protein production technologies could contribute to food security through improvements to consumer agency, resilience through diversification, and potentially, environmental sustainability (Chapter 3). Table 7.6 reviews the areas where atypical protein production technologies could impact food security.

Table 7.6 Atypical protein production and food security

	Technology	Potential	Requirements
Agency	Atypical protein production as a whole	• Diversification of the protein industry offers a greater range of consumer choices to address various concerns and preferences	• Appealing flavour, texture, and appearance • Comparable prices to other protein sources • Requisite infrastructure and technology to support scaling up • Desired by the consumer
Stability	Atypical protein production as a whole	• Improved resiliency of Canada's food system, anticipation of future changes to protein consumption and sources	• Appealing flavour, texture, and appearance • Comparable prices to other protein sources • Requisite infrastructure and technology to support scaling up • Appropriate food safety regulations in place
Environmental sustainability	Plant-based proteins as meat alternatives	• Lower GHG emissions per kg of protein	• Appealing flavour, texture, and appearance • Comparable prices to other protein sources
	Cultured meat	• Decreased use of water and land, fewer GHG emissions, less eutrophication in water bodies	• Testing and research into the reality of these claims; note there is no current commercial production with which to test • Overcoming significant technical and logistical barriers to achieve commercial scale, including continued progress in engineering biology • Integration with renewable or green sources of energy for all stages, including construction, supply, and operational needs

Shifting consumer preferences, anticipation of future shocks, and improving the resilience of Canada's food sector are reasons to advance atypical protein technologies

The future demand for atypical protein production in Canada will likely be influenced by changes in diets and consumer preferences related to sustainability, animal welfare, personal health, and affordability. The alternative protein production methods discussed in Chapter 3 may contribute to consumer agency by increasing the product choices available. Furthermore, these technologies may increase resilience to potential future shocks related to climate change or market instability. In the panel's view, a protein portfolio approach providing diverse protein choices to consumers would contribute to Canada's ongoing leadership and resilience in the food sector.

Barriers to growth in some types of atypical protein production in Canada include challenges relating to funding and regulatory uncertainty

The initial costs for certain types of atypical protein facilities are substantial due to the size of facilities and skilled workers required, among other factors. This, combined with uncertainty around economic sustainability and consumer interest, presents substantial commercial risks to developers and suggests that policies or financing models for conventional production may be inadequate to foster innovation in atypical protein production (Section 5.2). Additionally, in some cases, novel proteins may challenge standard regulatory processes for food safety and labelling, as health benefits and risks differ widely from those of conventionally produced proteins, adding to the above challenges (Fernandez *et al.*, 2020b; U.S. FDA, 2022; Mridul, 2024).

> In the panel's view, a protein portfolio approach providing diverse protein choices to consumers would contribute to Canada's ongoing leadership and resilience in the food sector.

7.3 Panel reflections

While atypical food production technologies hold promise for diversifying the food system in Canada, it is clear that no single technology or type of production facility will meaningfully address all components of food security, particularly on a national scale. Innovations and advancements in atypical food production technologies are also subject to social, economic, and resource-related trade-offs, which must be considered alongside any potential benefits. Governments and decision-makers will have to determine which aspects of food security they wish to focus on, understanding that addressing food insecurity in Canada will largely not be achieved through the technologies discussed in this report.

Nonetheless, the areas in which atypical production technologies have the greatest potential to support food security are through agency, stability, and sustainability (though the impacts on social sustainability are understudied). Atypical food production could increase the resilience of the food system through diversification, and so could support Canada's ability to feed its population, be sustainable and innovative, and rely less on imports. In these aspects, geography and cultural context are critical, as technologies that may improve stability or sustainability in certain locations will not in others without significant support and resources. Furthermore, the desired scale of impact is important; when considering the stability of the food system, a container farm in a remote community may have a larger impact on local residents when compared to a sizeable cellular agriculture facility located elsewhere, but the latter will have a greater impact at the national level. Regardless of scale, however, many of these technological advancements in atypical production will not progress or achieve their stated goals without adequate enabling technologies and conditions, particularly access to renewable and affordable energy sources.

The panel emphasizes that the implementation of these technologies offers benefits outside of food security. A focus on technological advancement in atypical food production could support innovation and develop expertise in globally relevant fields, supporting job creation and greater economic prosperity in addition to a diversified food system. Importantly, greater expansion of atypical food production technologies and facilities should be considered complementary to conventional food production, which is evolving and advancing on a parallel track. Diversity in the agricultural production sector is key to enhancing Canada's resilience in the face of 21st century challenges brought forth by growing populations combined with limited resources, climate change, and other global problems. The technologies and production types discussed in this report support this diversity when working alongside other food production methods. Crucially, no one type of production can wholly replace the others, and the food system of the future requires them all.

Appendix

This appendix lists some commonly used technologies for CEA in Canada. Table A.1 provides a non-exhaustive list of technologies and references describing and examining them. A full discussion of the benefits and limitations of these technologies is out of scope for this report; however, listing these technologies is valuable as context for the novel technologies discussed in Chapter 2.

Table A.1 Common technologies deployed in CEA facilities

Category	Technology	Relevant references
Covering materials	• Glass (rigid panels) • Polyethylene (PE), low-density polyethylene (LDPE); film • Ethylene and vinyl-acetate (EVA; film) • Polyvinyl chloride (PVC; film and rigid panels) • Other flexible films: Polyester, Tedlar, Mylar • Polycarbonate (PC; rigid panels) • Acrylic • Anti-reflective coatings	Urban & Urban (2010); Castilla (2013); Ma *et al.* (2023); Maraveas *et al.* (2023); Wei & Chen (2023)
Artificial lighting	• High-pressure sodium (HPS) lamps • Metal halide (MH) lamps • Fluorescent lamps	Brechner & Both (2013); Lopez & Runkle (2017); Kusuma *et al.* (2023); Wei & Chen (2023)
Water and nutrient delivery	• Hydroponics—deep flow technique/raft mobile system, nutrient film solution, gutter system, sub-irrigation • Aeroponics • Aquaponics • Disinfection systems (e.g., UV, thermal, ozone, biofilter/wetland, chloride, peroxide) • Plant growth-promoting microorganisms or biostimulants	Ferrarezi *et al.* (2015); Dorais *et al.* (2016); Son *et al.* (2016); Eldridge *et al.* (2020); Lubna *et al.* (2022); Dhawi (2023)
Temperature, humidity control	• Hot water boilers • Solar sensible heat storage system • Active heat storage • Natural ventilation for dehumidification • Mechanical ventilation (e.g., fans) • Cooling pads • Heat pumps • Solar chimney	Cuce *et al.* (2016); Hassanien *et al.* (2016); Misra & Ghosh (2018); Ghoulem *et al.* (2019); Hemming *et al.* (2019); Arbaoui *et al.* (2023); Wei & Chen (2023)

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Category	Technology	Relevant references
CO_2 generation	• Atmosphere ventilation • Compressed CO_2 • Carbonaceous fuel burning • Chemical reactions with bicarbonate • Compost fermentation for CO_2 generation	See references in Wang *et al.* (2022)
In situ power generation and renewable energy	• Conventional photovoltaic modules • Combined heat and power generation • Biomass • Methane from landfill • Thermal energy from industrial processes • Geothermal energy	Hemming *et al.* (2019); Wei & Chen (2023); see references in Kumar *et al.* (2022)

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