Agriculture Technology Adoption

Current Adoption and Barriers

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The agricultural sector is a major contributor to Canada's economy and will continue to have an important role in the years ahead. In 2023, the sector employed 2.3 million people, representing one in nine jobs, and contributed $143.8 billion to the GDP. Agriculture encompasses a broad range of activities, with primary agriculture generating the highest GDP per capita and foodservice contributing the least. As technology will continue to transform agricultural practices, recognizing the technological needs, and how they differ across enterprises and workforce segments, will be essential for the sector's long-term performance.

Agricultural innovation and invention

Canada is a global leader in agricultural innovation, with a market value of $954 million in 2021, but adoption of technologies varies by enterprise size and ownership, and policies often respond to climate and market pressures instead of proactively driving innovation. Some notable examples of innovation in agriculture are as follows:

- **Controlled environment agriculture (CEA):** Greenhouses, vertical farms, and other enclosed production systems have undergone significant growth through technology-enabled solutions (e.g., smart watering systems), with current digital tools projected to generate an additional $750 million to $1.5 billion in annual revenue.
- **Data aggregation platforms:** Powered by artificial intelligence (AI) and Internet of Things (IoT), these systems consolidate information from multiple sources (e.g., crop monitoring, fertigation, and irrigation systems) to automate climate controls, improve energy efficiency, and enhance crop outcomes.
- **Sensor technologies:** Environmental sensors monitor soil, air, and crop conditions, enabling irrigation, climate control, and automated harvesting. Lower costs are making these tools more common across operations.
- **Nutrient and water delivery systems:** Precision irrigation and nutrient delivery, especially in CEA, enable more efficient use of resources. Smart greenhouse systems can cut water use by up to 90%, and vertical farms by as much as 98%.

> **Soil and growth mediums:** These systems can improve crop growth and reduce land needs, offering flexible options for rural and Indigenous communities.

> Renewable energy systems: Solar, geothermal, wind, and bioenergy can support production where access to utilities are limited. Renewable energy production on farms has nearly doubled since 2015.

> **Robotics and autonomous farming:** In CEA, robotics improve cultivation outcomes while reducing labour needs, which account for 31% of greenhouse costs.

> **Germplasm modification:** Innovations in germplasm strengthen crop resilience to climate challenges, helping overcome seasonal limits.

> **Biostimulants:** Support crop health and provide pest control.

Determinants of technology adoption

Adoption of technology in the agricultural sector is shaped by a combination of factors. While innovations are transforming production, smaller and equity-deserving agribusinesses often face barriers that limit their ability to benefit from new technology. The key factors that influence technology adoption are as follows:

> **Capital:** High costs for technology and training are a significant barrier to adoption, especially for small and equity-deserving-owned enterprises. Exacerbated by geopolitical events and trade tariffs, rising input costs are adding greater pressure. Moreover, technological innovations are often designed for those with greater resources and capacity to adopt them. As a result, these tools tend for smaller businesses.

> **Education:** The agricultural workforce has long relied on intergenerational knowledge transfer, which risks widening skills gaps as technology advances. Without training and understanding of clear economic benefits, agribusiness entrepreneurs may be hesitant to adopt innovations. As such, technological tools that integrate easily with existing practices see better uptake. While skills training initiatives exist, targeted training for small agribusiness and equity-deserving entrepreneurs are limited, and there is a need for more flexible programs such as microcredentials, specialized certificates, and work-integrated learning opportunities.

> **Technology applicability:** Because agricultural innovation is driven by intensive R&D, technologies are often designed for large enterprises with the capacity to invest in and implement them. Small and medium-sized enterprises (SMEs) are rarely the focus of new inventions, leaving them less engaged and with fewer opportunities to participate in innovation. As a result, much of the emerging technology has limited applicability to their operations.

> **Infrastructure:** Adopting data-driven systems requires fast, reliable Internet, yet only 59.5% of rural households and 42.9% of First Nations households on reserves have high-speed access. This gap is keeping many rural, older, and Indigenous-led agricultural enterprises from fully participating in the digital shift in farming.

> **Policy:** Supporting smaller and equity-deserving agribusinesses in adopting new technology will require policy updates, such as addressing interprovincial trade barriers that limit market access as well as tax changes to encourage value-added activities.

Conclusion and recommendations

While Canada's agricultural sector has many technological innovations that are improving efficiency and scalability, the analysis shows that their benefits are not equally distributed. Key factors influencing adaptation tend to favour larger enterprises, potentially widening the divide rather than levelling the field. As such, the following recommendations are proposed:

*While Canada's agricultural sector has many **technological innovations** that are improving efficiency and scalability, the analysis shows that their **benefits are not equally distributed**.*

> Funding initiatives should focus on targeting SMEs and enterprises owned by equity-deserving groups to cover capital costs and access technology skills training.

> The agricultural sector needs to be positioned as a field with diverse career opportunities. This includes addressing cultural, sectoral, and gender-based stereotypes, promoting technological and managerial roles, and highlighting and encouraging the leadership of women and equity-deserving groups in innovation, sustainability, and emerging areas such as vertical farming and agri-tourism.

> Education and skills-training opportunities need to be broadened to improve accessibility, and this can be done through microcredentials, specialized certificates, and work-integrated learning tailored to the needs of the sector.

> Concomitant wraparound supports for training and education are required to ensure access for equity-deserving entrepreneurs. This includes Internet access, which remains a key barrier for Indigenous Peoples. Other proven supports include fee waivers, mental health services, as well as child care and family support.

Context

Agriculture sustains the Canadian economy, and sector innovation is important to continue improving market opportunities, ensuring local self-sufficiency, and sustainability. In 2023, Canada's agriculture employed 2.3 million individuals, providing one in nine jobs nationwide, and contributing about $143.8 billion to Canada's gross domestic product (GDP).[1]

Canadian agriculture enterprises include various primary and supporting business activities, including foodservice (about 20.5% of agriculture sector GDP), food retail and wholesale (about 25.1% of agriculture GDP). These activities supplement primary agricultural production (about 21.3% of agriculture GDP), food and beverage processing (about 24.0% of agriculture GDP), as well as work done by inputs and service suppliers (i.e., agronomists, nutrient and fertigation suppliers, technology sellers) (around 8.9% of agriculture GDP).[2] Across the food production supply chain, primary agriculture (about 142 K GDP per capita), food and beverage processors (about 112 K GDP per capita), and input and service suppliers (174 K GDP per capita) have the highest GDP contribution per capita, where food retailers and wholesalers (about 58 K GDP per capita), as well as foodservice providers (31 K GDP per capita) are marginal direct GDP contributors, though are requisite constituents of the Canadian agriculture and agri-food value chain.[3]

Successful integration of technology into agricultural entrepreneurship requires understanding the needs gaps in implementation by small, medium and remote agriculture and agri-food enterprise as well as the needs of diverse agricultural entrepreneurs and workforce participants. Research from McKinsey shows about 81% of large farm operations either use or plan to use at least one digital agriculture tool, above adoption by medium-sized farms (2,000 to 5,000 acres) at 76% and smaller farms (under 2,000 acres) at 36% of operations.[4] Agriculture technology usage is markedly lower among Indigenous Peoples and equity-deserving groups, thus requiring interventions to ensure agriculture and agri-food market prosperity.

The last century of agriculture primarily involved raising animals and commodities, fixing machinery, and simplified value-added enterprises to farmed materials. Technology-driven agricultural entrepreneurs are increasingly specialized, and focused on management in the selecting, outsourcing, and optimizing of expertise rather than performing the necessary labour themselves. Agricultural technology is changing which people are drawn and poised to be successful, and creates a unique opportunity for new agriculture entrepreneurs to enter the sector and address skilled labour shortages following either their interest and or expertise to manage a technologically sophisticated operation.

Technology in Canadian agribusiness

Technology and cost reduction strategies are transforming the agriculture and agri-food sector value chain as the sector changes. However, progress is slow. Changes in farming are often incremental, typically precipitate from transformational inventions gradually as the invention is applied to different contexts or iterated upon.[5] Generally, technology has allowed management of larger farming operations. Over the last 70 years, the average farm size has more than tripled to an average of 315 hectares,[6] while livestock operations have intensified to nearly a 20 times increase in operation size over the same time period.[7] Moreover, systems automation in food and beverage processing has reduced downstream costs in restaurants and food service, and seeks to address Canadian consumer habits including reductions of food purchasing from restaurants (about 41% of consumers), choices of less expensive restaurants (about 38% of consumers).[8]

> *Research suggests that the majority of Canadians (about 62%)* ***opt for a lower-priced import over more expensive domestic products****, despite interest in domestic production (about 46% of consumers).*

Innovations in food and beverage need technology as it allows enterprise to pace with import market prices. Research suggests that the majority of Canadians (about 62%) opt for a lower-priced import over more expensive domestic products, despite interest in domestic production (about 46% of consumers).[9] Given that nearly 70% of food consumed in Canada is grown and processed in Canada, technology-enabled cost savings may ensure high utilization of domestic production and drive sector growth.[10, 11]

Despite growing skilled and unskilled labour deficits, the Canadian agriculture and agri-food sector is benefiting from technological advancements.[12] For instance, the Canadian Agri-Food Policy Institute forecasts that the current digital tools for in-field and controlled environmental agriculture like greenhouses could boost productivity, improve enterprise competitiveness, and reduce environmental impacts, while unlocking a further $750 million to $1.5 billion in annual revenue for Canadian agribusiness.[13] The Canadian Genomics Institute estimates that cellular cultivation and precision fermentation could support an additional $18.8 billion toward Canadian GDP.[14]

Continued investment and innovation in the sector is necessary to abate the impact of job vacancies, which are predicted to generate a $3.1 billion annualized sector loss.[15] A variety of technologies are now common in rural, urban and controlled indoor agriculture environments. These include autonomous guidance and equipment steer, crop sensing, harvesting (including crop grasping), smart watering and nutrient supplementation. The invention of new sensors and technologies (e.g., electrochemical sensor monitoring, image-based herd analytics), as well as the AI-enabled integration of data sources for informed decision making, has the potential to transform the agricultural sector in food production, processing, and provisioning.

This report reviews the current adoption of agriculture and agri-food technologies across sectors, which includes digital (cloud data management platforms, predictive farm models), precision agriculture (GPS, autosteer, and precision fertigation), as well as common (use of environmental and climatological sensors) and new innovations. These technologies span food production (e.g., creation of biostimulants and innovative pest control using AI-image detection), food manufacturing (e.g., new biocomposite materials), and preparation for market (e.g., smart purchasing and resource allocation platforms for grocery providers and distributors). This report examines how the agriculture and agri-food sector is being transformed by technologies, the barriers to technology adoption for small and diverse operations and sector workers. It identifies several means forward through skills training to improve digital and artificial intelligence (AI) literacy, as well as data and technology education and thus adoption.

Agricultural Innovation and Invention

Introduction

Canada is a global leader in agriculture and agri-food sector innovation, recognized with a market value of $954 million in 2021 from $617 million in 2016.[16] However, there are more technologies available than currently being used, with notable differences in adoption across enterprise size and diversity in ownership. Canadian farmers and agricultural operations are left to respond to global competitors, as opposed to lead against competitors who advance by proactively integrating digital technologies into enterprise to tackle challenges related to rising input costs, climate related risks, and market transitions.[17]

The disparities in technology adoption are caused by structural and systematic barriers, including regulatory frameworks such as the Sustainable Canadian Agricultural Partnership, which do not place sufficient focus on ensuring equity and the proactive adoption of agricultural technological innovations. In Canada, agricultural technology policy is positioned reactively, responding to climate-related pressures, including changing precipitation, temperature, and extreme weather events, only then accelerating innovation adoption in field agriculture as the economic burden from a lack of participation reduces business viability and market competitiveness.[18, 19] It is only following the threat of tariffs from the United States has the Canadian Government launched more extensive support for agribusiness, however, funding is reactive to offset costs of export and not in capacity building.[20] Intentional equity and proactive policies in agricultural

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continued invention and innovation is crucial to maintaining Canadian market competitiveness. While Canadian agriculture is increasingly diversifying to improve market differentiation, such as in the role immigrants play in supporting operation succession among Canadian farms,[21] continued, proactive, and explicit support are needed to improve sector participation and technology adoption.

The following section of the report will review current agricultural technologies and new innovations used across agriculture and agri-food enterprises.

Technological innovation in agriculture

In agriculture, innovation is often considered as the invention of new ideas, as opposed to the adoption of new tools, crops, or techniques (e.g., harvesting machinery, germplasm modification, and agronomy-guided planting strategies).[22] By this definition, innovation is notably high in the farming sector.[23] While invention usually occurs among large corporations, often making platforms narrowly applicable to large agriculture and agri-food business, small operation farmers are still innovators, even if they may not be filing many patents. Canadian farmers are among the biggest users of Internet of Things (IoT) technologies,[24, 25] and have undergone extensive adaptation of their enterprises through value-added services to adapt and diversify, and ensure resilience in their enterprise.[26, 27] In Ontario, 2018 taxation amendments provided new opportunities for operation expansion through farm retail opportunities, such as farm stores, and value-added production facilities, including local goods preparation and subsequent direct-to-consumer sales, and agri-tourism, including farm stays, tours, and other recreational opportunities.[28] It is upon innovation that existing processes are revisited, adapted, and then inventions are iterated from small innovations into real-world farming practices.[29] Several agricultural innovations are discussed herein:

Controlled environment agriculture (CEA)

CEA includes traditional glass and polyethylene and -carbonate facade greenhouses, in addition to indoor vertical farms, as well as other indoor enclosed production environments (e.g., modular shipping container farms, grow chambers).[30] CEA as a technology is a host platform to extensive fertigation, irrigation, as well as chemical, physiological and biological sensor technologies. The Canadian Agri-Food Policy Institute forecasts that the current digital tools in controlled environments (i.e., greenhouses) boost productivity, improve enterprise competitiveness, reduce environmental impacts, and carry the potential to unlock a further $750 million to $1.5 billion in annual revenue for Canadian agribusiness.[31] In Canada there are nearly 920 commercial CEA installations, which have contributed to agriculture and agri-food sector growth.[32, 33]

Canadian greenhouse operations have undergone significant growth to address urban production needs and resource limitations in rural and remote agriculture production, attendant to technology-enabled improved cultivation outcomes. Greenhouse farming accounts for about 39% of Canadian produce value, and about $2 billion in value for the Canadian horticulture industry.[34] Traditional greenhouse systems with smart watering controls already save up to 90% in water consumption with reduced footprints.[35] Technology-enabled turnkey vertical farming units improve efficiency to about 98% less water and 99% less land usage.[36] Improved operational efficiencies in cultivating within CEA begin to address the key economic barrier identified by Farm Credit Canada for young and immigrant farmers.[37] Further, when growing in a CEA, cultivation can utilize reduced organic matter amendment and arable land, supporting flexible rural agricultural enterprise. This may be of interest to Indigenous communities, where land designations on reserve and community land may prevent land use for agriculture.[38]

Data aggregation platforms

Agriculture and agri-food entrepreneurs are familiar with a variety of technologies, including crop monitoring, fertigation, and irrigation systems. However, unfamiliarity arises in the integration of multiple data sources. Data aggregation platforms are becoming essential for driving agricultural innovation and integration of innovative technologies. Applications of artificial intelligence (AI), the Internet of Things (IoT), and data analytics are supporting sustainable and cropping advancements.[39] AI and data-integration technologies can integrate data on external and internal environments and automate climate automation controls to improve energy efficiency and cropping outcomes in controlled environment agriculture systems. The so-called Internet of Things (IoT) is made up of hardware components like sensors, actuators, gadgets, appliances or machines designed for applications that are capable of transmitting data over the Internet or other networks.[40] IoT technology is a highly applicable platform for AI models,[41] as physical locations and data collected by moisture sensors, crop locations, irrigation valves and volumes, plant masses, among others, are transformed into online objects to be monitored or remotely controlled in crop and easing tasks that otherwise require farm labour.[42, 43]

Sensor technologies

In field and indoor agriculture environments utilize a variety of environmental sensors for soil and air moisture, and temperature monitoring,[44] as well as vision-based systems for crop, disease, and pestilence monitoring. Soil moisture sensors have historically been used to guide more effective water management—which improves efficacy in the 70% of the world's freshwater used for irrigation[45]—ensuring watering occurs at the right rate, time, and place relative to cropping needs. Most often, soil sensors measure the dielectric constant of the soil using capacitance technology, among other methods of infrared remote sensing, dry-weight methods, tensiometers, and neutron probing.[46] Air humidity sensors also inform cropping practices, enabling decision-making regarding irrigation,[47] providing data for fenestration and ventilation systems in controlled environment agriculture systems and livestock operations,[48, 49] and to minimize disease and pestilence through ensuring humidity levels are not conducive to infection.[50, 51, 52] Temperature and environmental control sensors are also extensively used in food and beverage manufacturing for quality assurance purposes.

Optical sensors are also commonly used across crop monitoring for phenology, tracking growth outcomes, and monitoring performance, presence of pests and disease, and monitoring product production. For instance, RGB cameras can be used to tag crops depending on their life history stage and

Software can integrate plant health monitors from vegetation indices and multispectral imagery from satellites, helping to ***forecast crop performance*** *and* ***address potential environmental challenges*** *for agriculture and agri-food operators.*

develop a harvesting plan for farm workers. An innovative workflow would involve crop detection which feeds into a farming sensor platform that has autonomous harvesting, so that coupled geotagged fruits can be collected with crop grasping technologies and ultimately reducing farm labour. In the field, these technologies are onboard many agriculture drones, orthophoto and satellite imagery providers, where large spectral and image datasets can be analyzed to monitor crops, optimize crop health, predict yields, and manage resources efficiently.[53, 54] In food production, these systems can be used to support accelerated manufacturing and ensure consistency in food processing and packaging. Building across these sensors, AI systems can integrate data for transformative practices. For instance, software can integrate plant health monitors from vegetation indices and multispectral imagery from satellites, helping to forecast crop performance and address potential environmental challenges for agriculture and agri-food operators.[55]

New sensors are also improving cultivation, through profiling biomarkers and microenvironmental parameters, and transducing bio-signals to electric readout for data analytics. Electrochemical crop signal monitoring technologies (e.g., Vivent® Biosignals), and non-invasive on-plant bio-based and biodegradable sensors. For detecting plant growth, onboard sensors can measure traits including cell expansion and elongation. Similarly, other sensors have been developed to measure transduction mechanisms for transfer of gases, liquids, and sugars throughout plant tissues.[56, 57]

Sensor price has depreciated due to mass production, promoting widespread adoption of this technology across agriculture and agri-food enterprises.[58] The innovative use of these technologies requires their linkage to sensor platforms that allow scalability with operations, and integration of new technologies as they are developed.

Nutrient and water delivery systems

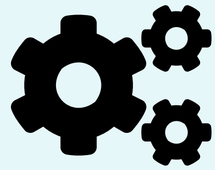
Precision irrigation and nutrient amendment systems are important to support optimized resource usage. Growing water and nutrient scarcity to support current production requires efficiencies, and these systems can ensure dosing at the right time, place, and form (e.g., liquid or granular fertilizer, broadcast foliar spray or drip to substrate).[59] This ensures dosing for maximized uptake, minimizing waste and thus potential environmental detriments from fertigation,[60] reduced resource expenditure, and optimized crop yields. Controlled irrigation and nutrient delivery systems are used in rural field and CEA agriculture, however automation and integration with other systems is more prevalent in CEA units. Traditional greenhouse systems with smart watering controls already save up to 90% in water consumption with reduced footprints.[61] Technology-enabled turnkey vertical farming units improve efficiency to about 98% less water and 99% less land usage.[62] Improved operational efficiencies in space and utilities begin to address the key economic barrier identified by Farm Credit Canada for young and immigrant farmers.[63] Using multi-sensor data infrastructure, crops can be continually monitored and environmental parameters recorded, including soil moisture. Irrigation schedules can be adjusted in real time, to ensure water is applied efficiently to enhance yield and resource use efficiency.[64, 65, 66]

Soil and growth mediums

The advancements in cultivation media are limited to CEA, as different systems have piloted various biochar-enriched substrates, peat-based, and spent material (coco-coir and wood fiber and bark products)[67, 68] as well as soilless systems like hydroponics and aeroponics. Ultimately, substrate and system selection will depend on the cropping optimization requirements for improving water retention, nutrient availability, and overall plant growth.[69, 70] When in a CEA, cultivation can utilize reduced organic matter amendment and arable land, supporting flexible rural agricultural enterprise. This may be of interest to Indigenous communities, where land designations on reserve and community land may prevent land use for agriculture.

Renewable energy systems

In remote and rural environments, renewable energy source integration and optimization, such as integrating across geothermal and solar power, supports agricultural production where access to utilities are limited.[71] Renewable energy systems are revolutionizing cultivation by making practice self-sustaining. Decreasing costs of solar technologies, now as the least expensive source of electricity generation,[72] have almost doubled the renewable energy production on farms from 2015 to 2021. Across operations of all sizes, nearly 11.9% of Canadian farms used at least one form of renewable energy.[73] Renewable energy includes bioenergy (about 2.9%), geothermal (about 1.9%), solar (about 7.7%) and wind power (about 1.0%).[74] In food production and packaging, sustainable and renewable energy sources are important to reducing overall environmental impact, valued for their cost efficiency and energy independence, especially in locations where remote production exists and access to electrical infrastructure is expensive and inconsistent.[75] Renewable energy and energy management systems (e.g., waste-to-energy, heat recovery) can further promote circularity in food drying, facility heating, evaporation, distillation, sterilization and pasteurization of food and beverage.[76]



In remote and rural environments, renewable energy source integration and optimization, such as ***integrating across geothermal and solar power,*** *supports agricultural production where access to utilities are limited.*

In the northern rural environments, limited daylight exposure may inhibit large-scale dependence on agrivoltaics (coupled with natural lighting and solar power generation), however, these environments have marked success with geothermal, passive heating. This can be used in residential, commercial, and industrial solar power systems, and also in remote locations where electricity access is limited.[77] Further, many of these technologies are broadly applicable to Canada's rural agricultural environment which is concentrated toward the southern border.

Robotics and autonomous farming

Robotics-led production is improving growing outcomes in harvesting, particularly in controlled environment agriculture, addressing growing short- and limited-term worker shortfalls over the last decade.[78] Worker labour remains the largest share of greenhouse expenses, accounting for 31% of average operation cost in 2019,[79] in crop protection and harvesting practices.[80, 81] Similarly, technology can address labour shortages in food production and packaging. The Business Development Council and Food Processing Skills Canada estimate about 142,000 vacancies by 2030 in roles such as case and box erectors (forming packaging vessels), packers, and palletizers (which prepare products for shipment)[82, 83]. Moreover, value-added industries have shown marked improvements in productivity and income following their investment in automation.[84] Robotics in agriculture and agri-food industry represents a sector shift from a predominantly labour-intensive industry and, through emerging methods, can improve upon natural processes such as self-pollination in vertical stacking farms.[85] In CEA, robotics has improved cultivation outcomes through disease and pest detection, and by supporting optimized crop monitoring.[86] AI-led disease and pest monitoring is especially useful for yield insurance in vertical farming units, as Health Canada, through the Pest Control Products Regulations, has not approved the use of pesticides in these controlled agriculture environments.[87]

*Robotics-led production is **improving growing outcomes in harvesting,** particularly in controlled environment agriculture, **addressing growing short- and limited-term worker shortfalls** over the last decade.*

Germplasm modification

Innovations in germplasm modification support crop innovation, address agriculture and agri-food sector workforce transitions, and respond to growing calls for climate resilience in production. Outdoor cultivation in Canada is limited by environmental variability and seasonality,[88] and CEA agriculture means crops can be grown year-round. Workforce limitations for seasonal cropping often rely on foreign workers for short-term work in CEA. Inconsistent employment opportunities mean sector vacancies are expected to increase by 34% over the next eight years, reaching almost 6,200 unfilled positions in 2030, up from the peak vacancy rate of 8.2% in 2022.[89] Innovations in germplasm research and development includes the development of "ever-bearers"—plant cultivars which consistently produce fruit, most notably among berry crops,[90] which offer the opportunity for increased and continued sector employment,[91] and more consistent paths toward citizenship for skilled foreign workers. Similarly, biotechnology-enabled crop germplasm research can support the development of climate-resilient genetic modified cultivars, with reduced irrigation requirements,[92] as supported through the federal Genomic Adaptation and Resilience to Climate Change (GenARCC) project.[93] Historically, germplasm research has been successful in reducing pests and pestilence among common row crops[94], and in modifying crops phenotype, cropping stages, and ultimately yields to meet Canadian cultivation goals,[95] despite concerns over gene flow, reduced crop biodiversity, and ownership laws for regulating genetic modification.[96]

Biostimulants

Biological-based innovations address fertigation requirements and disease and pest management (as biocontrols).[97, 98, 99] Biostimulants are humic and fulvic acids (for soil or cultivation substrate amendment), used for nitrogen-sequestering compounds and atmospheric-nitrogen fixers, beneficial bacteria and fungi (e.g., mycorrhizal fungi and endophytic fungus species), and in pest control and management.[100, 101, 102] Biostimulants can also be used directly into food and beverage processing, such as seaweed and botanical extracts into beverages, to improve consumer marketability.[103]

The adoption of existing innovations, and the ability to invent and adapt practices to new technologies, rests on adequate technological, digital skills and AI literacy training for sector participants. Furthermore, it requires addressing intersectional barriers that impede access to training, resources for implementation, and systematic biases in how technology is incorporated within agriculture and agri-food sectors.

Determinants of Technology Adoption

Introduction

There are a variety of social, economic, technical and policy facets that influence the inequitable adoption of agricultural technologies across enterprises. The biggest factor impeding the adoption of technologies is the cost of agriculture technologies and services.[104] Many agriculture technology platforms are not geared toward smaller and diverse agriculture and agri-food enterprises.[105, 106, 107, 108] They are more conducive to larger scale operations with the organizational capacity to employ specialists. Where technology is supposed to level the playing field among enterprise size, technological innovation adoption in agriculture and agri-food sectors is driving a digital divide. As larger operations adopt technology, their capacity to scale their operation and effectiveness increases, and with growing market share they are the focus of new agricultural and agri-food technology inventions. Additionally, Indigenous Peoples, equity-deserving groups, as well SMEs in agri-food and agribusiness often lack general digital and AI literacy, as well as specialized technical skills to understand technologies and assess their value case to existing operations and support their implementation where applicable. This section explores the requirements of technology adoption in the agriculture and agri-food sector.

Determinants of technology adoption

Capital requirements

The primary deterrent of adoption is raising costs of production, which work synergistically with adverse capital costs in the implementation of technologies, the costs in developing skills training for small and diverse agricultural and agri-food sector entrepreneurs, and the cost of maintaining technological systems.

Farm operation expenses have been increasing for producers in Canada, and subsequently downstream industries in the value chain of food and beverage processing, and food service.[109] In 2018, production expenses for feed increased by 9.4%, and on-farm labour prices have increased by 7.3%.[110] Farms are generally becoming more cost-efficient,[111] though it is unclear whether rising fertilizer costs subject to global geopolitical events, including Russia's invasion of Ukraine, and tariffs for export to major trade partners in the United States and China, will continue to affect cost effectiveness and thus downstream sector costs.[112, 113, 114, 115] Ongoing economic agribusiness uncertainties in export and raw material acquisition, coupled with agricultural enterprise support mechanisms, may implicate whether businesses will continue to improve their expense-to-revenue ratio. These may be felt among SME agriculture and agri-food enterprises where alternative suppliers and production contingency plans are limited.[116]

The cost of technology and new capital assets (e.g., tilling machines, packaging equipment) is inhibiting many SMEs from adopting innovative technologies. In Canadian food and beverage processors (nearly 7600 enterprises), the majority of businesses are SMEs (about 91% of industry).[117] Given capital limits, they lack sufficient resources to support innovation adoption.[118] Where low-cost operational efficiencies can be realized, agricultural SMEs operations lead in adoption, including shifting crop production and rotational cycles to improve yield output (e.g., wheat to canola without a summer fallow crop).[119] SMEs and diverse agri-preneurs are not adverse to technology and innovation but limited by their capital to implement existing innovations.

Educational requirements

The cost and applicability of educational skills determines which individuals have access to education and thus their ability to understand, use, and innovate using technologies in the agricultural sector. When prospective workers seek upskilling, it is often at their own personal expense, which may hinder barriers to entry into more technological agriculture and agri-food sector roles. While no-cost initiatives exist, such as the newly created Upskill Canada and Government of Canada initiative to train agricultural technology, agri-food and advanced manufacturing sectors on technological skills,[120] free training is often sector generalized and does not account for workforce considerations. Skills-training is needed to support sector participants to adopt new technologies, improve operation efficacy, and support technology innovations that combat rising costs through operational cost reductions and potential scaling opportunities, thereby maintaining the Canadian agriculture and agri-food markets' competitiveness.

The agricultural workforce in Canada has traditionally relied on intergenerational transfer of knowledge and farming techniques within farming families.[121] Family-transferred and observational farming knowledge, while inherently valuable, does not provide readiness and skills for adopting new, technology-driven practices in modern farming.[122] Relying solely on generational knowledge will widen the skills gaps over time, as older generations may not be as familiar with new tools that are integral to furthering future adoption and younger generations may be more reliant on generational knowledge transfer while being more open to embrace innovation and agricultural technology advancements.[123]

Skills training initiatives exist, though, targeted training programs for SMEs and diverse agriculture and agri-food entrepreneurs and workers are limited. Skills training is often led by university and college certificate programs, and generalized to the sector.[124, 125, 126] Research by the Future Skills Centre supports the need for more diversified education and skills training opportunities, including micro credentials, specialized certificates, and work-integrated learning at agricultural and agri-food business firms.[127]

*The agricultural workforce in Canada has traditionally relied on **intergenerational transfer of knowledge** and farming techniques within farming families. Family-transferred and observational farming knowledge, while inherently valuable, **does not provide readiness and skills for adopting new, technology-driven practices in modern farming**.*

In the absence of trained staff and entrepreneurs, the incorporation of technology in the agriculture and agri-food sector requires contract technical specialists to support automation. SMEs and diverse agriculture and agri-food enterprises using contractors also compete for skilled labour to implement technologies, which may further delay automation and the integration of new technologies.[128] While primary labourer needs might lower, there is greater demand for those with higher skills and education to support an automation transition without extensive dependence on outside trades.[129]

SMEs and equity-deserving group workers and enterprises recognize the value of technology,[130] but realizing benefits requires additional non-technical education to understand technology compatibility and perceived benefits of new innovations.[131] Technologies that complement and align with pre-existing farming practices or allow for seamless integration bolstering compatibility improve adoption rates. Precision agriculture technologies that incrementalize current knowledge and systems—such as GPS systems or integrate with machinery without operational disruption—are easier to trust and use for farmers, and help potential adopters perceive benefits more clearly compared to completely novel systems.[132, 133] To evaluate new technologies by their relative cost, productivity, and efficiency, farmers need to understand not only what the technology does, but also the operational considerations to integrate it into their enterprise. Skills using on economic forecasting tools or decision-making frameworks are increasingly important for technology adoption, beyond just knowledge of a technology and how it works.[134] Certain technologies are more intuitive for adoption, and farmers and agri-food businesses are more willing to invest when they see clear economic returns.[135] For instance, dairy farmers have reported feeling surprised by the expectations of computer literacy required to use technologies, and unfamiliarity with how to interpret data outputs.[136] Nearly 95% of agriculture data and insights is generated in unstructured raw data formats, where SMEs and agriculture entrepreneurs lack the skills to organize and adapt this data to inform operations.[137] Smaller operations are less likely to collect data or follow insights from technology platforms as they may not understand outputs. Further, many associate mistrust in data storage and use by large corporations, and the lack of skills to use the technology.[138, 139]

Skills and knowledge gaps demand training designed to address competencies required for agriculture and agri-food sector workers, enabling them to realize the potential of new digital technologies and harness the benefits. Several competency frameworks for agriculture and agri-food workers exist but disproportionately target field cropping and livestock rearing skills.[140, 141, 142, 143, 144] Technical competency for value-added services, and production and manufacturing in agri-food, are less defined. RBC has identified several technical skills needed for Canadian agriculture into the future, including digital expertise, leadership, and critical thinking to manage large operations among owners and operators; technological skills to tool and task robots, write code, understand and implement software for farm equipment technicians; as well as specialized expertise through advanced education in areas including genetics, artificial intelligence, as well as advanced imaging and machining.[145, 146] The need for training in using these tools are a recognized barrier that slows adoption and reduces confidence in agronomic recommendations. Comprehensive agricultural skills are required to boost digital literacy and on-farm readiness that will increase trust and confidence in new proven forms of technology.[147]

Initiatives like Innovation Farms enable researchers, innovators, industry leaders, entrepreneurs, and professionals to test, validate and demonstrate digital agriculture technologies and innovative advancements on a 5,500-acre commercial farm in Manitoba. This lowers the perceived risk that is typically posed for producers by providing tangible tools and furthering skill development to empower relevant stakeholders to evaluate the return on investment and make informed decisions before fully committing to adoption.[148] The Canadian Agri-Food Data Initiative, Enterprise Machine Intelligence Learning Initiative (EMILI) provides data literacy training courses to equip farmers and producers with foundational knowledge and data governance skills related to agriculture data.[149]

There is a lack of small companies generating ***technologies geared for small and medium-sized enterprise (SME)****, remote operations, and/or those run by equity-deserving groups. When these groups are* ***not the targets of inventions****, they are subsequently* ***not engaged.***

Technology applicability requirements

Agricultural inventions often occur in intensive R&D environments led by researchers and those with extensive scientific and engineering backgrounds and are often geared toward larger agriculture and agri-food organizations with specialized expertise.[150, 151] The lack of technology adoption can be attributed to economies of scale on smaller farms. There is a lack of small companies generating technologies geared for small and medium-sized enterprise (SME), remote operations, and/or those run by equity-deserving groups. When these groups are not the targets of inventions, they are subsequently not engaged, which limits their ability to participate in innovation.[152, 153, 154] Rarely do agricultural technologies begin in a barn and not a boardroom: for instance, CATTLEytics, a women-led agricultural technology company is one of the few dairy farm technologies that is built by a farmer, offering data-driven tools including digital twins, protocol development, and analytics to assist farmers in enhancing efficiency, sustainability, and profitability without being cost-inhibitive.[155] Instead, most technologies are generated by large telecommunication, food production, and medical enterprises.[156, 157, 158]

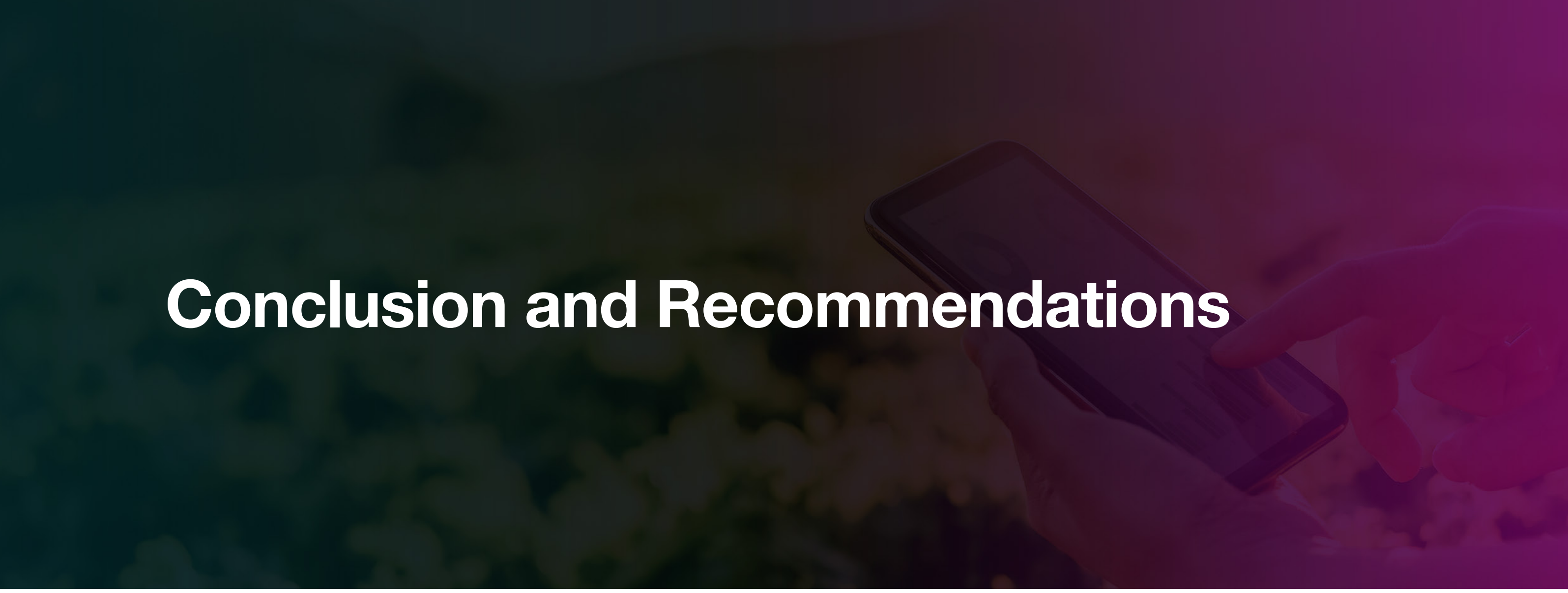
Infrastructure requirements

The lack of infrastructure, namely the lack of Internet, and thus restricted access to flexible skills training and general market connectivity, exclude many older farmers, rural communities, and Indigenous Peoples-led agricultural and agri-food enterprises from the digital revolution in agriculture[159, 160] In rural Canada, where about 72.2% of oilseed and grain farms and about 93.6% of dairy cattle and milk farms are located,[161] technology access is limited by unreliable broadband and Internet services. Persistent digital infrastructure gaps significantly hinder the uptake of new digital technologies.[162] To support adoption of agricultural technological systems that produce large amounts of data, operators need high Internet speeds and low latency connections.[163] The government of Canada introduced the Universal Broadband Fund in 2020 with an initial budget of $1.8 billion which has grown to $3.2 billion, aimed to connect 98% of Canadian residents to high-speed wired Internet by 2026 and reach all Canadians by 2030.[164] However, even in densely populated provinces like Ontario, farmers residing only 20 minutes outside of major urban cities report significant connectivity and reliability issues that cannot be afforded when running systems in farming operations.[165] In 2021, only 59.5% of rural households and 42.9% of First Nations households on reserves have access to high-speed Internet,[166] with lower rates among farmers of which 90% reside in underserved rural areas.[167] Access for Indigenous Peoples and equity-deserving groups, as well as small and medium-sized agri-food and agribusiness to technological innovation requires continued investment into improving Internet and broadband access.

A technology innovation focus is central to the Canadian Agricultural Innovation System strategy which emphasizes mobilizing inventions "from the lab to the marketplace,"[168] though, disproportionate focus of innovation by financial and information technology sectors focuses on larger operations,[169, 170, 171] creating missed opportunities on profitability and sustainability gains among smaller operations.[172, 173] Higher levels of education and digital literacy among operators reduce the perceived complexity and need for extensive training, whilst lower levels pose a notable barrier toward adoption.[174] This will lead potential adopters to attempt trials and pilot experiments with the innovation on a small scale before committing to full adoption, reducing perceived risk.[175] Further, community support, peer networks, and trusted advisors (i.e., agri-retailers, extension agents, suppliers) and agronomists[176] are important as agriculture and agri-food sector enterprises will often look to community evidence of success before following "industry-leading" practices.[177]

Policy requirements

Policy change is also needed to improve the adoption of innovative technologies by SMEs and diverse-owned agriculture and agri-food businesses. For instance, interprovincial trade barriers limit market access for major agricultural sectors such as livestock production and processing.[178] Changes to taxation structures on operations, such as in Ontario,[179] may enable agricultural enterprises to expand into value-added services and improve the diversity of their expertise and offerings, including in areas such as food processing, agritourism, and secondary production mechanisms such as bottling or packaging.[180] As technology expands global market access for agri-food and agriculture businesses, support for new technologies may offset the disproportionate burden of geopolitical and trade conflicts. Global geopolitical conflicts including the Russian invasion of Ukraine have increased the costs of fertilization, irrigation, and feed to support primary production. Similarly, tariffs are limiting the market for Canadian exports to the United States and China, which are substantial consumers of agri-food and seafood products, as well as commodities and meat production.[181, 182, 183] Additional regulation improvements are needed in controlled environmental agriculture to evaluate whether the current ban on pest control products remains necessary,[184] as crops in controlled environmental agriculture can still fail following disease and pest proliferation.[185] Improvements to technology adoption will require a series of policy changes, namely that target interprovincial legislation differences and redundancies, new health and safety standards for technologies as they develop, and attention to policies which may be discriminatory toward Indigenous Peoples and equity-deserving groups, limiting their sector participation and the market value they generate.



Conclusion and Recommendations

Conclusion

Our analysis indicates that Canadian agriculture is facing a variety of challenges. The adoption of technology across the agriculture and agri-food sector—from production to processing, to sale—has the potential to continue growing Canadian agricultural export market competitiveness, while substantiating local communities and self-sufficiency in production. Encourage workforce participation of technically proficient and skilled workers, helps address urgent labour shortfalls driven by changes to the Federal temporary foreign worker policies and estimated at about 24,000 workers, as well as the need for operator succession as nearly 40% of Canadian farm operators expected to retire by 2033.[186]

A variety of social, environmental, and economic aspects intersect to implicate how technology is adopted within the agriculture and agri-food sector, and particularly by diverse-owned agriculture and agri-food SMEs. Our research shows technology platforms are not designed toward SMEs in the sector, but rather large commodity and livestock operations, as well as large food and beverage manufacturers. Purpose-built technologies for large operations often come with the high capital and maintenance costs for agricultural machinery, software platforms, sensors and data products, which can deter technology adoption among SMEs and diverse-owned agribusinesses. Data and technical knowledge gaps among operators may further a digital divide between small and large institutional agribusiness, as SME operators may be unable to understand how a technology works, or to calculate the value proposition for their enterprise, where the diverse and specialized expertise among large corporations supports timely cost-benefit analysis of technologies. As such, there is a need for an increase in the number of agricultural technologies geared toward SMEs and diverse-owned enterprises. At large, when technical skills are encouraged and stereotypes are rectified, opportunities emerge for small AgTech innovators to develop tools that scale across enterprise sizes.

Recommendations

To improve agriculture and agri-food sector participation as the sector undergoes a technological transition requires several interventions. The following section revisits the previous Conference Board of Canada recommendations for a successful transition in traditional field and livestock operations.[187] Beyond field agriculture, we provide recommendations for improved technology adoption across the agriculture and agri-food sector, with specific attention to the barriers to adoption by Indigenous Peoples and equity-deserving groups that participate.

Access to capital

Access to capital remains the single most important determinant of technology adoption among agriculture and agri-food businesses. Systematic integration of agriculture into Federal core funding allocations, and proactive funding for innovation is needed to prioritize the sector. Dedicated funding allocation, infrastructure investments, and policy changes are needed to recognize agriculture's role in national economic growth, food security, and rural development. The lack of explicit funding support for technology skills development, or for purchasing and maintaining operational assets, such as new tractors, sensors, and data platforms has made agricultural operations solely responsive, not proactive. Global competitors are advancing their market competitiveness through their proactive adoption of digital technologies. Funding initiatives need to help SME and diverse-owned operations offset the cost of capital procurement and should provide funding for targeted development initiatives for different equity-deserving groups to participate in skills training. In some cases, immigrants with advanced agricultural qualifications, including PhDs, are adversely underemployed, exemplified by cases of immigrant agriculture PhDs driving taxis in Toronto due to barriers like unaffordable farmland.[188] Indigenous Peoples are also limited in their ability to access capital, as the Indian Act continues to impose restrictions that hinder reserve activities, including S.89 that limits using land as collateral to finance capital purchasing of innovative technologies, and S.87 which complicates structuring businesses on-reserve.[189] Additional and flexible financing opportunities to specific groups are needed to improve access to capital and thus sector participation.

Address sector stereotypes

Cultural, sectoral, and engendered stereotypes remain embedded in the agriculture and agri-food industry, perpetuating the representation of agriculture as a low-income labour practice and not a potentially high-income and skilled one with extensive workforce opportunities. When temporary-foreign workers are only used to meet low-skilled labour requirements,[190] Canada limits the potential innovation capacity driven by skilled immigrants who are interested in agriculture careers,[191, 192] resulting in elevated sector transitions and high employment turnover, subsequent labour shortages, and thus limited enterprise growth of agribusiness. Retention of immigrant workers in primary agriculture and agri-food industries is closely tied to their skill level, with higher-skilled individuals more likely to remain in the sector long-term.[193] As technology evolves the potential agriculture and agri-food sector careers, continued promotion of the diverse opportunities and expertise in the sector is needed.

Generally, the workforce in Canada is often unaware of agriculture and agri-food sector opportunities. The workforce needs proficiency in reading and interpreting data, and not necessarily those without a background in agriculture but rather those who have interest and expertise manage technologically complex operations.[194] Concomitant demand for specialized agronomic and technological skills is needed to support the innovation of biotechnologies, upon higher-level expertise and knowledge

of soil, agronomy, crop science, biomedical science, machinery and technology fabrication and implementation, software development, and analytics.[195, 196] Continued promotion of the role of farming and food production, and the diversity of career opportunities emphasizing technology, data and AI literacy as well as managerial expertise in the workforce is needed.

Further, resolving engendered stereotypes that women garden and men farm require continued support to ensure sustained momentum among women in agriculture who are innovative and sustainable,[197, 198, 199] who lead in emerging technologies around urban and vertical farming, and agri-tourism,[200, 201] and who have tighter and more robust support networks than men in the agri-food sector that help facilitate sector-wide transitions without disproportionate advancement of different social, economic, and cultural groups.[202, 203, 204] Successful implementation will require illustrating how diverse agriculture and agri-food professionals are leading in addressing global food security, building local self-sufficiency, promoting environmental sustainability and resource management to help recruit new and younger talent to the sector.

Education for modern agriculture

Skills training is needed to ensure that SMEs and diverse-operators and workers increase technology adoption and thus maintain market competitiveness. Exposure to sector careers, and ensuring appropriate skills, requires continuous alignment of educational offerings to sector developments. Skills training programs in university and college certificate programs exist,[205, 206, 207] but diversified education and skills training opportunities in microcredentials, specialized certificates, and work-integrated learning at agriculture and agri-food firms are needed to meet educational constraints of diverse-owned and small agribusiness.[208, 209] Training programs need to be cognizant of the lateral, multi-faceted role operators and workers in SMEs and diverse-owned enterprises occupy, as compared to the capacity for specialized and vertical knowledge that exist among larger agricultural and agri-food institutions. Collaboration between agriculture and agri-food institutions as well as educational institutions will promote work-integrated learning opportunities and encourage continuous alignment of training initiatives with sector requirements.

Wraparound supports

Concomitant wraparound support for training and education initiatives is needed to improve technology adoption in the agriculture and agri-food sector among these groups. Infrastructure access to Internet and technology, capital supports to participate in training programs, and educational program flexibility in pursuing education begin to address the disproportionate lack of entry and lower income benefits following graduation of agriculture and agri-food programs for women, Racialized People, people with disabilities, and Indigenous Peoples.[210] Wraparound supports with proven success include offering more flexible and or hybrid learning, fee waivers, tailored education programs to cultural contexts, mental health services, child care and family support to better support Indigenous Peoples and equity-deserving groups to participate in agriculture and agri-food sector upskilling initiatives.[211] Further guidance for SMEs is needed to support technology adoption, as they often lack the organizational expertise to implement new technologies, even when workers have or have attained digital and technological skills through educational programs and or upskilling initiatives.

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