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Northern greenhouses: Knowledge review and innovation prospects for decarbonizing northern food systems

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1. Introduction

The Québec Northern Territory (TNQ) begins north of the 49th parallel and extends north of the St. Lawrence River and Gulf.[1] The Northern Regional Energy Ecosystems (EERN) are based on carbon-efficient innovations with a low environmental footprint. The EERN also seek to ensure basic services such as housing, food, health, and education for the TNQ's 63 communities, of which 31 are Inuit, Cree, Innu, and Naskapi—representing one third of the 130,000 residents. The TNQ's food systems do not adequately meet population needs, and food insecurity rates are the highest in the province, especially in Indigenous communities.[2] This situation stems primarily from political, economic, and social factors linked to the colonization of the TNQ, compounded by distance, climate change, and inadequate infrastructure.[3,4]

According to the *Northern Action Plan (2023–2028)*, food security is the main justification "to continue developing greenhouse projects adapted to the climatic conditions of northern communities."[5] Greenhouses are plant production infrastructure designed to capture heat and control climate parameters, thereby creating a more favourable microclimate and extending the growing season. They produce fresh fruits and vegetables that help meet part of the TNQ population's nutritional needs. Their role must be considered in synergy with other modes of indoor and outdoor production as well as traditional food sources such as hunting, fishing, and gathering. Greenhouses also promote education and strengthen social ties by providing spaces for meeting and learning.[6] During consultations held in four municipalities in Eeyou Istchee James Bay, participants expressed a desire to equip their communities with greenhouses and to acquire the skills required to operate them.[7] In this synthesis, we will review the state of knowledge and key factors so that northern greenhouses can rise to the dual challenge of contributing to the TNQ population's basic needs in food, health, and education, as well as the decarbonization of their food systems.

Depending on soil and climate conditions and local history, different forms of plant production are practised. Outdoor crops have been and continue to be grown as far north as Chisasibi, above 53°N.[8] Indoor cultivation is also conducted in container farms[9] such as those in Kuujjuaq[10] and Inukjuak.[11] We identified 44 greenhouses in the TNQ[12]: 6 in Nunavik, 9 in Eeyou-Istchee James Bay, and 29 in the Côte-Nord region. Based on agreements between local partners, various distribution systems have been implemented: 45% rely on sales, while the rest distribute produce free of charge to gardeners or community organizations. Indeed, only 9 of these greenhouses are owned by private or family businesses; the majority are community-based or have a social mission. They contribute to the production of local, high-quality, and affordable food, to strengthened social connections, and to greater collective capacity.[6] They also promote reintegration and the creation of local jobs.[13,14] Gardening itself can contribute to users' health and well-being, though few studies have explored this from the perspective of First Nations or Inuit communities.[15] The educational mission is broadly shared; this is the primary role of greenhouses managed by school institutions.[6] Several community greenhouse projects also actively take part in research programs,[16,17] and two greenhouses are directly managed by research institutions.[18,19] To fully assess the contribution of northern greenhouses to decarbonizing food systems, it is essential to consider the specific governance of these projects so as to mobilize communities, respect their right to self-determination, and ensure the sustainability of their food systems initiatives.

2. Greenhouse Project Governance and Sustainability

Ensuring the long-term sustainability of projects is a central component of decarbonizing food systems, to offset the financial impacts of installing infrastructure and to maximize long-term benefits for communities.

2.1 Social Entrepreneurship

Social entrepreneurship (SE), which aims to create social value,[20] is particularly prominent in TNQ greenhouse projects because traditional agricultural entrepreneurship is often not viable and because these projects provide a wide range of social services within communities.[6] SE plays a crucial role in revitalizing northern communities, which often face economic decline and geographic isolation.[21,22] This isolation, along with limited support ecosystems, represents a barrier to developing commercial agri-food businesses.[23–25] Collective decision-making also has deep cultural roots, particularly in Nunavik, reflecting the central role of cooperatives in the region's economy.[26,27] Despite the dynamism of SE, a dual challenge exists: increasing community members' involvement in projects[6,28] and strengthening managers' capacity for action through the participation of administrations, non-profit organizations (NPOs), and businesses that support their work.[23] Examples include regional health boards [29–31] that help finance certain food-related initiatives, or Hydro-Québec, which guarantees the purchase of a portion of Radisson's greenhouse production.[32]

2.2 Importance of Managers

Northern greenhouse projects face significant management challenges, mainly due to the heavy workload borne by a small number of often-isolated individuals.[33] Agri-food projects often emerge thanks to the determination of "champions"[34]—highly motivated individuals who succeed in rallying their community around a project. These individuals represent an important driver of development, helping to spread both skills and knowledge,[35] as illustrated by the role of the Gaïa solidarity cooperative[36] in developing agriculture in the TNQ. However, these individuals risk burnout,[6] and their departure often jeopardizes the sustainability of projects if no one replaces them or if the transfer is poorly managed.[13,37] Support that is tailored to local contexts and rooted in culture, while fostering individual engagement and leadership within collective dynamics, is essential to sustaining these initiatives.[23,38]

Hiring managers to ensure the proper functioning of infrastructure is a factor that supports project sustainability. However, the shortage of trained agricultural workers, high staff turnover, and lack of funding make recruitment difficult, especially for community projects in remote northern communities.[6] Involvement of community members in governance (boards of directors, cooperatives) and in project activities (collective work, social gatherings) strengthens sustainability, since it reinforces a sense of responsibility and ownership over the infrastructure.[38,39] Citizen mobilization within projects, however, remains a challenge, especially when the people leading the projects are not originally from the target communities.[7,40,41]

2.3 Long-Term Funding Beyond Start-Up

Community projects depend heavily on stable funding and a favourable regulatory environment. Most of these organizations lack the revenue required to cover the salary of a manager and the operating costs of a greenhouse.[6] At the start-up stage, the social mission of these projects often provides access to grants that can fund infrastructure—costs that would be difficult, if not impossible, to offset through revenues from product sales alone. Over time, a manager's salary is covered mostly through social activities, funded by grants, service revenues, or drawn directly from the organizations' mission-based operating budgets. Initiatives supported by a strong network of local partners are more financially stable and better aligned with community needs. Strategic collaboration with governments, research centres, and businesses is essential for the sustainable development of greenhouses, ensuring that they meet community needs while supporting their long-term viability.[13,33,42,43] In several communities, it is the involvement of local governments (band councils, local administrations, municipalities) that ensures the start-up, coordination of initiatives such as community food development plans,[44] and the funding of employees.[19]

2.4 Research and Innovation In the TNQ Context

The involvement of First Nations and Inuit remains insufficient in both research and governance linked to food systems and climate change adaptation,[28,45] despite increasing awareness within academic and institutional settings. This undermines the engagement of these communities in innovative northern agricultural projects.[38] Such projects are often perceived as colonial initiatives that fail to meet community needs. Establishing trust-based relationships is essential in Indigenous research contexts.[46] Several research approaches have been documented,[47] such as "research as ceremony,"[48] the "two-eyed seeing" approach,[49] or conducting research "in a good way."[50] However, these methods remain almost non-existent in the scientific literature in the fields of engineering, energy, and infrastructure development.[47]

Trust-based relationships and democratic governance are equally important for the non-Indigenous communities of the TNQ. Collaborative innovation approaches for the entire TNQ include "living labs," which allow local actors to steer research so that it responds to their needs.[51,52] This approach is also relevant in supporting regions in sustainable EERN transition, provided that the living labs remain centred on people and their local contexts, with the aim of building their skills.[53] Co-construction approaches described as "situated"[54,55] and "community-based"[56] are also particularly relevant for analyzing regional features and local agri-food initiatives.[21] It is equally important to promote collective discussion processes such as consensus decision-making,[57] as well as dialogue as a method of knowledge transmission[15] in research projects with both Indigenous and non-Indigenous communities.

3. How Greenhouses Help Decarbonize Northern Food Systems

The colonization of Canada's northern territories shaped both the food systems and energy supply of Indigenous and non-Indigenous communities.[4] In the TNQ, food systems are dominated by imports, with a smaller and variable contribution from hunting, fishing, gathering, and local production.[58–60] For example, a study in James Bay reported that 91.2% of respondents obtained food from the local grocery store; 57.1% shopped outside their community; 50.9% engaged in hunting, fishing, and/or gathering; and 40.3% practised gardening.[61] The sedentarization of Indigenous communities and the establishment of non-Indigenous settlements came with the construction of permanent infrastructure, leading to the use of diesel generators and fuel-oil heating systems.[56] Today, 18 TNQ communities are not connected to the electrical grid, including 15 in Nunavik, which increases their reliance on fossil fuels. Overall, the TNQ lies at the very end of global food distribution chains, which have a high energy footprint due to intensive use of fossil fuels, fertilizer production, transport, and food preservation.[41,62]

There is little available data on greenhouse gas (GHG) emissions associated with TNQ food systems. A 2018 study estimated that transporting food from distribution centres to Nunavik generated 1.8 kg CO_2eq per kilogram of vegetables.[41] It is well established that transporting food to northern communities contributes to the environmental footprint of the food system significantly, due to the remoteness of production and distribution centres. However, the lack of data on food production and processing, dietary patterns, and waste management prevents a comprehensive GHG emissions assessment for the northern food system.[38,41,58]

Local greenhouse production could help reduce dependence on imports, and in turn, the GHG emissions linked to food transport. On average, greenhouse production in southern Québec generates 3 kg CO_2eq/kg of fruit and vegetables and 1.3 kg CO_2eq/kg of leafy vegetables. Heating is the main contributor, accounting for about 68% of GHG emissions in greenhouse production. Using propane raises emissions to 4.9 kg CO_2eq/kg of fruit and vegetables. Renewable energy reduces emissions to 1.1 kg CO_2eq/kg of fruit and vegetables for electricity-based heating, and 1.6 kg CO_2eq/kg of fruit and vegetables when heated with biomass.[63] This highlights the importance of designing greenhouses that require less heating or that incorporate technologies to improve energy efficiency. That said, the lack of data on other significant factors, such as infrastructure and input supply, limits the ability to produce a full GHG emissions assessment of TNQ greenhouse production.

In northern regions, however, local food production is about more than reducing dependence on imports and lowering carbon footprints. Above all, it provides fresh produce that residents would otherwise not have access to. Long supply chains and difficult transport conditions mean that some foods never reach the TNQ, or if they do, they arrive unfit for consumption.[24] In this sense, local production contributes to the right to food by giving people access to healthy, fresh, and affordable food.[13]

4. Climate Control and Energy Efficiency in Northern Conditions

Greenhouse production enables the control of certain climate parameters and the protection of crops from adverse weather such as early or late frosts and strong winds. Climate control is central to greenhouses' contributions to the EERN in helping limit GHG emissions.

4.1 Climatic Conditions

Climatic conditions affect both the type of greenhouse structure that can be built and the costs of heating or the length of the growing season in the case of an unheated greenhouse. For example, in 2023 the frost-free growing season lasted about four months in Québec City, compared with three months in Havre-Saint-Pierre or Chibougamau, and just two months in Kuujjuaq. It is worth noting as well that the coldest temperatures recorded were –42.8°C in Kuujjuaq and –34.1°C in Québec City.[64] Levels of solar radiation also affect the passive heat gain and solar capture capacity of greenhouse structures. For instance, day length at latitude 47.30° is about 15.6 hours on June 21, compared with 22 hours at latitude 65° on the same date. In midwinter (December 22), the reverse occurs, with only 8.3 hours and 3.3 hours, respectively.[65] These environmental parameters must be considered in planning any year-round greenhouse production.

It should also be noted that both current and future climate change will profoundly modify northern growing conditions, likely extending the production season and increasing yields.[66] Based on the degree-day requirements for cereal crops, research has estimated that by 2100 the climatic limit for cereal production could shift northward by an average of 500 km, and up to 1,200 km in some regions.[67] While this overall increase in degree-days generally represents an advantage for both outdoor and greenhouse northern production, greenhouse climate management in the TNQ will also need to anticipate increasingly frequent heatwave episodes, such as during the summer of 2023[6] when temperatures in the Radisson greenhouse stayed above 30°C for several weeks.

4.2 Climate Control and Energy Efficiency

Optimal temperature settings are based on light availability and the type and growth stage of the crop (vegetative versus generative). In the TNQ, passive heat accumulation within greenhouses is limited, depending mainly on solar radiation and outside temperatures. Energy efficiency refers here to reducing the amount of energy (especially fossil or non-renewable forms) required for agricultural production.[68] To limit the energy footprint and heating demands of northern greenhouses, it is essential to prioritize greenhouse structures and technologies that reduce heat loss, maximize solar radiation capture, and enable energy storage. Adopting crop management practices adapted to unheated or minimally heated greenhouses is another option consistent with the principle of energy efficiency (see Section 5.2 Crop management). However, supplemental heating is often indispensable for ensuring favourable climatic conditions beyond the summer season, making a focus on low-carbon heating sources essential.

4.2.1 **Maximizing Solar Gain And Reducing Heat Loss**

Greenhouse orientation, geometry, and type of cladding directly affect solar gain and heat losses. Some removable technologies can also be used to limit heat loss.

Regarding orientation, the optimal direction depends on the intended production period. For year-round greenhouses, an east-west orientation, with the long side facing south, maximizes solar capture in winter.[69,70] By contrast, for summer-only production, a north-south orientation is generally preferred.[71] Site selection must also consider protection from prevailing winds (and the possible use of windbreak hedges), which significantly influence convective heat loss through greenhouse walls.[72]

Among single-span greenhouses, five geometries tend to be studied the most: quonset, vinery, modified-arch quonset, and symmetrical or asymmetrical gable-roof types.[6,70,73–75] Most of these models already exist in the TNQ, but few studies have focused on their energy efficiency.[76] Regardless of latitude, asymmetrical gable-roof greenhouses capture the most radiation, while quonset greenhouses capture the least.[74,77] However, greater thermal losses in asymmetrical gable-roof models make them less efficient overall.[73] Existing geodesic dome greenhouses in the TNQ[76] better distribute loads and withstand wind, but they are more complex to build, pose sealing issues, and are not well suited for large surface areas.[78] The passive solar greenhouse (also known as a Chinese greenhouse) is another interesting model, consisting of a solid north wall to reduce thermal losses (through radiation and conduction/convection) while maintaining solar gain.[72,79] Such walls also store excess daytime heat and release it at night.[80,81] While showing strong potential for energy efficiency, there are, to our knowledge, no passive solar greenhouse models with insulated north walls in the TNQ.[76] Commercial availability of structures is a determining and sometimes limiting factor for innovation in greenhouse geometry. More simulation-based and experimental studies would be useful to inform design choices in this area.

Greenhouse cladding, necessarily translucent, is usually made of glass, rigid plastic, or polyethylene film.[74] For optimal heat performance, cladding materials should have high transmittance for visible and ultraviolet wavelengths, but low transmittance for infrared.[72] Their resistance to radiation-induced opacity over time should also be assessed.[74] Choosing cladding with good thermal resistance, or using double-layer coverings, also reduces heat loss.[82] Polycarbonate is among the most thermally efficient materials; double layers reduce heat loss by 30–35% compared with glass greenhouses.[72] Possibly due to cost, the most common model among diversified vegetable growers in Québec is the double polyethylene layer.[71] Finally, thermal blankets or screens, often installed along the walls, can reduce heat loss by at least 20%, especially at night.[69,72,82] This approach has also been adapted in low-tech single-span greenhouses for diversified vegetable production, ensuring fall and winter leafy green crops in Québec.[83,84]

4.2.2 **Maximizing Energy Storage**

Storage systems can be used to maintain thermal conditions in greenhouses despite drops in temperature. They operate on the principle of capturing heat when it is warm (during the day, or more seasonally during summer) and then releasing it when it is colder (at night or in winter).[72,77,85] Most systems use sensible heat storage. Other methods, such as latent and chemical storage, exist but are not yet commercialized, and their use would involve handling potentially polluting residual materials.[16,77]

Sensible storage systems can be passive, using volumes of water (in barrels or ground-level reservoirs), rocks (built into a wall or other elements of the greenhouse), or masonry.[72,79] Active storage systems also exist, such as soil storage or rock-bed systems (a bed of rocks placed under the crops). In these systems, a heat-transfer fluid circulates through the soil or between the rocks.[77,85] Such systems are already being used successfully in single-span greenhouses in Kuujjuaq and Radisson.[76]

By combining different methods of passive heating, solar capture, and insulation, annual heating demand could be reduced by as much as 50% in southern Québec.[33]

4.2.3 **Alternative Heating Sources**

Supplemental heating is sometimes necessary in greenhouses. Since heating accounts for 65% to 85% of total energy use, the choice of energy source has a major impact on the carbon footprint of production.[72] Data from greenhouses in the TNQ are incomplete, but about one third of recorded heating systems run on fossil fuels (propane or fuel oil).[12] The rest rely on electricity, biomass, or geothermal energy.[76]

Several renewable or low-carbon alternatives are already in use or under development. One promising option is the recovery of industrial waste heat, which is already being successfully implemented in the TNQ. For example, the only year-round commercial greenhouse in Chapais is heated by steam from a cogeneration plant.[76] Biomass heating is another suitable option in regions like the TNQ where forestry residues are abundant. This well-established method is used by both small and large greenhouse operations.[86,87] Another renewable source is solar thermal energy, which is used to heat water or air that is then recirculated in the greenhouse.[88] Wind energy could also be used, but it would need to be combined with other energy sources to ensure a stable supply.[88] Heating electrification is another alternative being promoted and subsidized by the Québec government, enabling the adoption of energy-efficient technologies such as heat pumps.[89] However, this is not a viable option for large parts of the TNQ where hydroelectric power is unavailable.[90] Geothermal heat pumps (GHPs) harness underground heat to warm or cool greenhouse air. A techno-economic assessment of GHPs in northern conditions found that, while the upfront installation cost is high, their low operating and maintenance costs and significant reductions in GHG emissions make them highly suitable for this production context.[91] In fact, a simulation of greenhouse heating in Kangiqsualujjuaq showed that GHPs could reduce fuel oil consumption by 40%.[92] Several alternative heating sources are therefore available, but technical and scientific support is essential to ensure that they are operationally feasible, energy-efficient, and sustainable over the long term.

4.3 Light Management

Plant growth depends largely on the amount and quality of light received. In agriculture, light is often measured as photosynthetically active radiation, or Daily Light Integral (DLI), which is the amount of radiation received in moles of photons per square metre per day (mol/m²/day) at wavelengths between 400 and 700 nanometres.[93] A DLI of 8 mol/m²/day is often considered the minimum required for certain leafy vegetables such as spinach and lettuce.[94] At the other extreme, continuous 24-hour light exposure can either support or hinder growth, depending on the crop species and the quality of light, with responses varying widely.[95,96] Current research is mostly based on trials conducted under artificial lighting, which limits how directly results can be applied in northern environments. Adding artificial lighting during dark periods, and using shading systems during the summer, could help optimize the amount of light received by crops throughout the year.

5. Greenhouse Crop Management in Northern Conditions

5.1 Soil and Growing Substrates

5.1.1 Soil Conditions

Very few soils in the TNQ have been characterized from an agronomic perspective. Northern soils are usually classified as podzols, retisols, cambisols, histosols, cryosols, or andosols, with podzols being the most common.[97] In the zones that have been studied in the Côte-Nord region, ferro-humic podzols dominate, with mesisols and humisols (organic soils) found along the shoreline.[98] Podzols are low-fertility soils characterized by acidic pH, low phosphorus content, and a sandy texture that limits their ability to retain water and nutrients.[99] Turbic cryosols, found for example in Kuujjuaq, are mineral soils containing permafrost within the first two metres of the surface, with structures reshaped by freeze-thaw cycles.[100] Cultivation is possible on soils with discontinuous permafrost and is already practised in places such as Alaska.[101] However, special care must be taken when cultivating these lands, since they are highly vulnerable to subsidence following thawing and drying.[66]

5.1.2 Amending Native Soils and Producing Growing Substrates

When possible, it is preferable to use local soil instead of importing growing substrates, in order to reduce both the economic and environmental costs associated with greenhouse projects.[99] However, soils with low horticultural potential require extensive interventions and amendments to improve their chemical, physical, and biological properties and ready them for cultivation.[99] For podzols, parameters such as acidity, cation exchange capacity (CEC), and organic matter content must be addressed on the chemical side, while water retention is a key physical factor. For biological conditions, commonly used indicators include overall microbial activity, microbial biomass, and taxonomic and functional diversity.[102] Some researchers also suggest that nematodes—key elements in the soil food web—are strong indicators for tracking the agronomic potential of northern soils.[103]

Adopting soilless cultivation is an attractive alternative, especially in areas with cryosols. Raised-bed cultivation with organic substrates is already being applied in several northern agricultural initiatives that aim to approach organic farming standards.[6] However, the vast majority of substrates are imported, adding to both ecological and economic costs. Very few studies have explored the production of substrates using local northern materials.[104] Sustainable substrate production requires that raw materials be chosen based on available local organic or inorganic resources as well as residual materials from nearby industries and the availability of local equipment and processing capacity.[105] Currently, organic greenhouse substrates are dominated by peat. Although it is affordable, effective, and available in northern regions, peat is non-renewable and has a high ecological footprint due to its biodiversity impacts and associated GHG emissions.[106]

Several locally available materials show strong potential as soil amendments or as components of growing substrates. The use of wood by-products (e.g., bark, fibre, ash, biochar), manure, industrial or municipal sludge, fishery waste, agri-food residues, and biomass from native plants are all promising alternatives to explore as substitutes for peat.[105,107] It is also essential to select conditioning methods for these inputs that minimize both energy and environmental costs, and to ensure that the technologies used are suited to the needs and capacities of local users. Using raw inputs, or materials that have undergone only simple processing such as shredding or secondary transformation such as composting, are options to prioritize, since they are inexpensive and relatively easy to implement in remote regions.[105] When importing materials is necessary, preference should be given to renewable and compressible products to reduce both economic and environmental costs.

Below, we outline several examples of raw or processed resources identified in the literature that have good potential in northern greenhouse contexts.

Residues from the forestry and pulp-and-paper industries are among the main resources available in the TNQ. A 2020 study on the Côte-Nord region estimated potential biomass availability at 882 kt/year from forestry, 64 kt/year from agriculture, and 37 kt/year from residual materials for bioenergy production. In Northern Québec, estimated availability was 976 kt/year from forestry, 35 kt/year from agriculture, and 37 kt/year from residual materials.[108] Shredded branches or sawdust have a high carbon-to-nitrogen ratio, which slows decomposition and can immobilize nitrogen, making it less available to crops when incorporated into soil. Composting *bois raméal fragmenté* (BRF; ramial chipped wood) is a promising alternative. Trials in northern conditions (Opitciwan at 48°N) successfully produced a suitable substrate for basil cultivation by composting BRF from green alder (*Alnus viridis* subsp. *Crispa).* Using fungi for conditioning also has the added benefit of producing a secondary harvest of mushrooms for food or medicinal uses.[109] Wood ash, a major by-product of the pulp-and-paper industry, contains 25–60% calcium carbonate and is typically used for its alkalinizing properties.[110] Numerous studies have shown that paper mill sludge can improve multiple physical, chemical, and biological soil properties. Its use can increase soil organic matter, reduce bulk density, strengthen aggregate stability, and improve water retention across different soil types and textures.[111] A study on northern podzolic soil found that sludge not only raised soil pH but also increased microbial biomass and respiration.[110]

Biochar is a material produced from plant biomass through pyrolysis, that is, the carbonization of residues at high temperatures (400°C to 800°C) in the absence of oxygen. Its high carbon content (50% to 90%) and recalcitrant nature make biochar an excellent amendment for carbon sequestration.[112] This carbon can remain stable in soils for 400 to 1,000 years.[113] Biochar can also be used to increase soil pH, improve water and nutrient retention, enhance soil porosity, and stimulate microbial activity. Due to its black colour, it can even affect albedo and help warm soils.[112,114,115] However, the optimal application rate and frequency, the choice of feedstock material, and the production method for specific functions remain open questions in northern conditions.

Residues from commercial fisheries can also be used as soil amendments and fertilizer resources. In 2020, 5,181 tonnes of products were landed from marine fishing in the Upper and Middle Côte-Nord and 5,260 tonnes in the Lower Côte-Nord, representing 22% of the province's total catch that year.[116] To our knowledge, the availability of residues in the TNQ, in terms of both volume and distribution, has not yet been quantified. Fish residues are rich in proteins and lipids, while shellfish residues contain 20% to 40% protein, 20% to 50% calcium carbonate, and 15% to 40% chitin, which is another source of organic nitrogen that can be used for its fertilizing and biostimulant properties.[117] Anaerobic digestion, fermentation, composting, pyrolysis, enzymatic hydrolysis, and drying are among the methods evaluated for treating fishery by-products.[117] However, the potential for high concentrations of heavy metals, salt, and microplastics requires monitoring and proper treatment before these residues can be used. Their recovery as agricultural amendments offers an environmental advantage for both the fishing and agricultural sectors.[118,119]

The recovery of household food waste is also an interesting option, particularly for community greenhouse projects. At present, several composting initiatives are already underway in northern communities. However, basic conditions such as reaching sanitizing temperatures (≥55°C), maintaining water content between 40–60%, and ensuring aerobic conditions through regular turning and the addition of a structuring agent to allow air circulation[120] are sometimes difficult to achieve with current composting systems. Government initiatives have supported the installation of industrial composting facilities in several northern communities.[121,122]

A more geographically detailed inventory, covering a broader range of potential inputs, would be needed to better define the resources available, depending on the location of the agricultural initiative and its soil amendment requirements. Experimental trials should also focus on making use of available local raw materials and low-carbon inputs while developing conditioning processes that require minimal equipment and infrastructure accessible to local communities. The goal is to produce effective and sustainable soil amendments and horticultural substrates adapted to northern contexts.

5.2 Crop Management

5.2.1 Crop Choice

Most of the crops typically grown in greenhouses on vegetable farms in southern Québec are currently cultivated during the summer season in the TNQ.[6,71] The choice about which species to grow must be based on local agropedoclimatic and cultural contexts, the type of greenhouse infrastructure, the available heating capacity, the level of technical expertise, and the availability of individuals involved in production, among other factors. When prioritizing energy efficiency, unheated or minimally heated greenhouses outside the summer season represent a potentially effective option. However, this is only feasible for a limited number of crop types, which do not always align with community food preferences.[83] Certain leafy greens, especially Asian crucifers such as mizuna, komatsuna, and bok choy, are well-suited to this method.[123] Greenhouse production could also ensure a year-round supply of native perennial crops such as *Qungulit* (mountain sorrel, *Oxyria digyna* (L.) Hill), a plant traditionally harvested by Inuit, which is already cultivated in greenhouses and containers in places like Inukjuak and Kuujjuaq.[6]

The development of northern agri-food systems cannot occur without the consideration and involvement of local communities, both to ensure that production meets their needs, interests, and tastes, and to address regional food sovereignty. Elsewhere in Canada, some First Nations have worked to identify the needs and priorities of the agri-food sector, as in the *Northern Agriculture Futures* project led by the Ka'a'gee Tu community of Kakisa in the Northwest Territories.[43] Apart from the food security strategy for Inuit Nunangat,[124] we are not aware of comparable work being undertaken in Québec, or at least not publicly.

5.2.2 **Cultivar Choice**

Very few, if any, vegetable varieties have been specifically developed for the northern Canadian context.[43] Choosing an adapted cultivar is nonetheless a key factor in successful production, as it helps farmers manage diseases, weeds, and climatic conditions specific to their context.[125] It is for this reason that varietal trials and farm-based selection projects are carried out annually in southern Canada and the United States.[126,127] As previously discussed, the TNQ's unique agropedoclimatic conditions necessitate specific varietal selection efforts. This is also true for greenhouse production, which although protected, continues to be shaped by distinctive regional conditions such as soil characteristics, light availability, and choice of inputs. In fact, many northern regions around the world have already developed their own genetic selection programs for crops of agricultural interest.[128,129]

5.2.3 **Fertilization Practices**

The physical, chemical, and microbiological properties of native soils affect nutrient availability, particularly phosphorus and the mineral forms of nitrogen most commonly absorbed by plants.[107] In organic greenhouse production, most nitrogen in fertilizers is organic, meaning that plant nutrition depends on microbial activity for ammonification and nitrification.[130] Some of the mineral nitrogen also comes from organic matter decomposition.[131] In northern soils, where microbial activity is reduced and organic matter content is either low or resistant to decomposition, the fertilization guidelines commonly used in Québec are probably not applicable.[132,133] These guidelines must therefore be adapted to assess external inputs of N-P-K and micronutrients, as well as the timing and frequency of applications, in order to maximize crop productivity while minimizing environmental losses. There is also a need to develop fertilizers that are specifically suited to northern conditions.[134]

5.2.4 **Pest Management**

Greenhouse production requires close monitoring of insects and crop pests, along with the capacity to respond quickly to limit damage and ensure satisfactory production levels. Greenhouse production in northern regions is affected by many of the same pests and plant health issues as those seen further south, although there is very little documentation on the subject. [6] Despite the geographic distance, plant diseases, insect pests, and weeds can still be introduced through food products, seedlings, growing inputs, or other vectors. The remote context of northern production makes pest management especially challenging. Ecological greenhouse production relies heavily on biological control, which involves introducing natural enemies (predators of pests) to control harmful insects.[135] Accessing these commercially sold predators is particularly difficult given the distances involved. Conservation biological control, which aims to encourage natural enemies already present by protecting their habitats, is another crop protection technique applied in greenhouses.[136] However, to our knowledge, there has been no systematic inventory of pest and disease problems currently observed in northern greenhouses, nor of the natural predators present and their potential effectiveness in northern greenhouse production systems.

6. Sharing and Sustaining Knowledge

Decarbonizing northern food systems requires the development and transmission of knowledge so that communities can master techniques and technologies and ensure the long-term viability of projects.

6.1 Poorly Adapted Training Opportunities in the TNQ

In some northern or Indigenous communities, agricultural knowledge has been lost or does not correspond to traditional food procurement practices.[15,43] Many TNQ greenhouse projects include workshops with elementary and secondary school classes. These activities are designed to promote healthy lifestyles[137,138] but also to build local gardening knowledge and generate interest in food cultivation.[139]

Research on the impact of school-based gardening programs remains limited. Online resources do exist, but there is little pedagogical content tailored to the specific pedoclimatic and sociocultural contexts of the TNQ. Accessing this information and putting it into practice remains a challenge.[6,140] Effective knowledge transfer and dissemination must be culturally adapted for each community[140] and integrated into reconciliation efforts.[15,141] In Indigenous communities, incorporating Indigenous languages and knowledge is a priority,[142] as is using traditional learning processes such as hands-on experimentation, observation, and imitation.[140] More broadly, several factors make knowledge transfer easier in community organizations: connecting learning to lived experience, spreading the process out over time to establish trust, emphasizing practical content that matches local needs, and ensuring the support of a social network around the learner.[143]

6.2 Knowledge Transfer for Project Sustainability

Greenhouse management requires specialized expertise.[6] One strategy used in a number of communities is to bring in external staff to start greenhouse projects or manage production.[39] While no study has examined the impact of these external hires on local capacity-building in the TNQ, the "networked rural development" approach suggests that skills need to be generated locally but enriched through interaction with external knowledge.[144]

Currently in the TNQ, basic training is sometimes provided by suppliers at the time of greenhouse installation. Organizations also offer agronomic and organizational support both remotely and through on-site visits.[36,145,146] However, the length of this support depends on funding, making long-term collaboration difficult.

Virtual professional training could greatly reduce travel costs and GHG emissions across the vast territory of the TNQ. However, this format alone is not sufficient to provide culturally adapted training or to transmit technical skills. To offer complete and engaging training, diverse methods are recommended, including collaborative learning approaches, the indigenization of training content, and methods that build socioprofessional integration skills.[141]

In the Côte-Nord region, the Baie-Comeau adult education centre, in collaboration with the Gaïa solidarity cooperative, recently began offering a semi-specialized vocational training program for agricultural labourers in horticultural production.[147] New models adapted to northern realities are also emerging, such as the

Ikajurtigiit solidarity cooperative, which supports apprentice carpenters in Nunavik by allowing them to accumulate hours toward obtaining their journeyperson certification.[148]

7. Conclusion

Northern greenhouse production offers strong potential for innovation in helping to decarbonize food systems in the TNQ. Greenhouses can play a central role within the Northern Regional Energy Ecosystems (EERN) by contributing to essential services such as food and health, including healthy lifestyles and mental well-being. They can also serve as safe spaces for learning and social interaction, especially when paired with community kitchens.

Heating requirements, along with the need to import soil and other inputs, are the main environmental impacts of greenhouses in the TNQ. Solutions are within reach to reduce these impacts by designing energy-efficient greenhouses that use storage systems, producing inputs and growing substrates locally, and promoting low-input agriculture through agronomic practices adapted to northern conditions. Ultimately, to ensure their environmental benefits over the long term, greenhouses must remain productive.

The key to long-term sustainability lies in the hands of northern community members themselves. Since community organizations are the primary drivers of innovation projects, it is essential that future research and development be directed by them, in both Indigenous and non-Indigenous communities. Only that approach can ensure development of the North, for the North, and by the North, in a way that respects the rights to food and self-determination.

Seedling workshop organized by Solidarité alimentaire Matagami (CISA, 2023)

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