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Evaluating Agricultural Sustainability in Newfoundland, Canada: Insights from a Data Envelopment Analysis (DEA) Approach

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Abstract:	This study evaluates agricultural sustainability in Western Newfoundland by assessing the technical, allocative, cost, scale, and environmental efficiencies of local farms using Data Envelopment Analysis (DEA). With an average technical efficiency score of 95%, most farms in the study area demonstrated effective resource utilization. However, disparities in allocative, cost, scale and environmental efficiencies highlight areas for improvement in optimizing input use efficiency and minimizing environmental impacts. Factors such as labor inefficiency, fertilizer overuse, and suboptimal scaling contribute to overall inefficiencies, while land optimization and quality seed use emerge as critical drivers of agricultural productivity and efficiency. A standout case study showcases a farm excelling across all efficiency metrics through sustainable farming practices, including no-dig methods, permaculture techniques, rainwater harvesting, integration of diverse farming operations, and composting. These practices reduce soil disturbance, enhance soil health, conserve water, and foster a circular economy. The farm exemplifies a holistic approach to sustainability, balancing productivity increase with environmental stewardship and serving as a model for other farming operations in the region. This research underscores the potential of advanced technologies, government support, and educational initiatives to promote sustainable agriculture in the Newfoundland and Labrador province. By incorporating efficiency metrics, this study provides actionable strategies to enhance both economic performance and environmental conservation. The findings emphasize the need for a balanced approach that optimizes resource use while minimizing ecological impact.

	Implementing these strategies can drive sustainable agricultural practices, improve farm resilience, and support long-term food security in regions facing environmental and socio-economic challenges.

Dear Editor,

I am pleased to submit our manuscript titled "Evaluating Agricultural Sustainability in Newfoundland, Canada: Insights from a Data Envelopment Analysis (DEA) Approach" for consideration for publication in *Renewable Agriculture and Food Systems*. This study assesses the sustainability of agricultural practices in Western Newfoundland by evaluating technical, allocative, cost, scale, and environmental efficiencies of local farms using Data Envelopment Analysis (DEA).

Our findings highlight the integration of DEA with environmental efficiency metrics to provide a comprehensive assessment of agricultural sustainability. While most farms in the study area exhibit high technical efficiency (95%), substantial disparities exist in cost, allocative, and environmental efficiencies. Key challenges include labor inefficiency, fertilizer overuse, and suboptimal scaling, while land optimization and quality seed use are critical drivers of sustainability. Additionally, we present a case study of a highly sustainable farm that employs no-dig methods, permaculture techniques, rainwater harvesting, and composting, exemplifying a balanced approach to productivity and environmental stewardship.

This research aligns with the scope of *Renewable Agriculture and Food Systems* by contributing an innovative methodological framework for evaluating farm efficiency and sustainability. Our study offers valuable insights into sustainable agricultural practices, resource use optimization, and policy recommendations aimed at enhancing agricultural resilience in the face of climate change and socio-economic constraints.

We believe this manuscript will be of interest to your readership due to its novel application of DEA in evaluating farm sustainability and its relevance to contemporary discussions on sustainable agricultural systems. This work has not been published elsewhere and is not under consideration by any other journal. All authors have approved this submission, and there are no conflicts of interest to disclose. The preprint version of this manuscript is available on SSRN: http://dx.doi.org/10.2139/ssrn.5127875.

Thank you for your time and consideration. We look forward to your feedback and the opportunity to contribute to the ongoing discourse on sustainable agriculture through your esteemed journal.

Sincerely,

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Title Page (with author details)

Evaluating Agricultural Sustainability in Newfoundland, Canada: Insights from a Data Envelopment Analysis (DEA) Approach

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Abstract

This study evaluates agricultural sustainability in Western Newfoundland by assessing the technical, allocative, cost, scale, and environmental efficiencies of local farms using Data Envelopment Analysis (DEA). With an average technical efficiency score of 95%, most farms in the study area demonstrated effective resource utilization. However, disparities in allocative, cost, scale and environmental efficiencies highlight areas for improvement in optimizing input use efficiency and minimizing environmental impacts. Factors such as labor inefficiency, fertilizer overuse, and suboptimal scaling contribute to overall inefficiencies, while land optimization and quality seed use emerge as critical drivers of agricultural productivity and efficiency. A standout case study showcases a farm excelling across all efficiency metrics through sustainable farming practices, including no-dig methods, permaculture techniques, rainwater harvesting, integration of diverse farming operations, and composting. These practices reduce soil disturbance, enhance soil health, conserve water, and foster a circular economy. The farm exemplifies a holistic approach to sustainability, balancing productivity increase with environmental stewardship and serving as a model for other farming operations in the region. This research underscores the potential of advanced technologies, government support, and educational initiatives to promote sustainable agriculture in the Newfoundland and Labrador province. By incorporating efficiency metrics, this study provides actionable strategies to enhance both economic performance and environmental conservation. The findings emphasize the need for a balanced approach that optimizes resource use while minimizing ecological impact. Implementing these strategies can drive sustainable agricultural practices, improve farm

resilience, and support long-term food security in regions facing environmental and socio-economic challenges.

Keywords: Efficiency metrics, resource use optimization, sustainable farming practices, environmental stewardship, DEA (Data Envelopment Analysis), Stepwise regression model.

1. Introduction

Agricultural productivity and efficiency are key metrics in farming policy development, serving as the foundation of sustainable agriculture by optimizing resource use to ensure food security, economic viability, and environmental preservation (Picazo-Tadeo et al., 2011). While often used interchangeably, these concepts differ, both rooted in classical economic growth theory (Solow, 1956). Productivity measures the ratio of agricultural output to input, assessing the amount produced by a give unit (country, sector or farm) using resources like land, labor and capital. Economic efficiency reached when “the marginal value of the inputs is equal to their respective unit costs” (Kelly et al., 1995), evaluates the return generated by using an additional input. Productivity growth stems from technological advancement, such as the introduction of chemical fertilizers during the Green Revolution, and to technical efficiency—defined as “the ratio of actual to best-practice production” (De Koeijer et al., 2003).

Historically, agricultural policies prioritized productivity through technological change, but recent research emphasizes improving efficiency as essential due to resources constraints and environmental concerns (FAO, 2017). Studies suggest that increasing technical efficiency, particularly in the use of polluting inputs such as pesticides, chemical fertilizers, and fossil fuel-based energy, directly supports sustainability by balancing 'economic and environmental objectives' (De Koeijer et al., 2003).

In Western Newfoundland, Canada, agriculture faces unique constraints, including acidic soils, a harsh boreal climate, and short growing seasons. Achieving production efficiency under these conditions is critical for sustainable agricultural practices (Keske, 2021; Reza and Sabau, 2022). Efficient farm management at the individual level is essential for the sustainability of an agricultural sector and broader agrifood systems (Soteriades et al., 2020). Farming efficiency is categorized into technical, allocative, cost, scale and environmental efficiencies, each addressing specific aspects of resource use and performance (Chankoson et al., 2020). Together these metrics offer a comprehensive framework for evaluating the agricultural performance of the studied farms and to identify sustainability pathways (Coelli et al., 2005; Pokhrel and Soni, 2017; Grzelak and Kryszak, 2023).

This study evaluates the economic, environmental, and social performance of local farms in Western Newfoundland using Data Envelopment Analysis (DEA) to assess their overall efficiency. The first objective is to measure the technical, allocative, cost, scale, and environmental efficiencies of farms in the region to determine overall resource-use effectiveness. The second objective is to identify key factors contributing to inefficiencies, such as labor use, fertilizer application, and farm size, to pinpoint areas for improvement. The third objective is to analyze the relationship between farm management practices and efficiency scores, highlighting how sustainable approaches impact overall farm performance. Given the boreal climate and acidic soils of the region, the study also assesses the influence of environmental factors on farm efficiency. Ultimately, the findings provide targeted recommendations for optimizing input use, minimizing environmental impacts, and improving long-term agricultural sustainability. By integrating these efficiency metrics, this research establishes a comprehensive framework for enhancing both economic viability and environmental sustainability in Western Newfoundland's agricultural sector.

2. Literature Review

2.1 The Concept of Agricultural Sustainability

From a purely anthropocentric perspective, which seeks to meet the food and fibre needs of the current generations without jeopardizing the capacity of future generations to do the same (WCED, 1987), sustainability in agriculture is a multidimensional concept defined by the three pillars of the Brundtland Commission's sustainable development concept—environmental, economic, and social—each of which is essential for ensuring the long-term viability of farming systems. Environmentally, sustainable agriculture focuses on preserving natural resources, enhancing soil health, conserving biodiversity, and mitigating harmful practices such as overexploitation of water and greenhouse gas emissions (Campanhola and Pandey, 2018; Muhie, 2022). Economically, it ensures that agricultural activities remain profitable for farmers, resilient against market volatility and climate variability, and capable of sustaining livelihoods (Pretty, 2008). Socially, it emphasizes equitable access to resources, fair labor practices, and the well-being of rural communities (Timmermann and Félix, 2015).

From a more holistic perspective, which sees sustainability not only as a theoretical concept about humans "living in harmony with nature and with one another" (Mebratu, 1998) over generations, but "as an objective feature of the world, a numinous condition that makes life on planet Earth possible and meaningful for this and future human generations", and "which implies that life in all forms is precious, it is worth sustaining” (Sabau, 2024), sustainability in agriculture receives essentially a new connotation. By viewing sustainability as an intrinsic value inherent in the interconnected systems of life on Earth, those practicing agriculture will pay attention not only to what humans can extract from the Earth or what they can dispose of as waste in the terrestrial and ocean environments, but how they need to participate responsibly in the maintenance of the life-web at the core of sustainability. The farm’s sustainability will be measured not only by its economic efficiency but also by its capacity to exist and function as a social-ecological system in the long-term (Ostrom, 2009, 2014). This requires scientific knowledge of how ecosystems work, and how humans can benefit by protecting the structures, functions, and processes specifically embedded in the ecosystems that sustain life, by organizing farming activities to work with nature and not against it, and by observing the laws of nature (Georgescu-Roegen, 1971) and the planetary boundaries (RockstrÖm et al., 2009; Steffen et al., 2015). It also requires changes in human behaviour enabling farmers to promote environmental stewardship and social cooperation. Some of the ethical principles that farmers need to consider for a life of sustainability are: contentment, which calls for living harmoniously within ecological limits; justice, which broadens the scope of fairness to include ethical obligations not only to their families and communities, but also to all forms of life; and meaningful freedom, advocating for responsible actions within ecological and moral boundaries (Sabau, 2024). Similarly, Felix Ekardt expands the sustainability discourse by emphasizing transformation, governance, ethics, and legal frameworks as critical dimensions which can be applied in practicing sustainable agriculture. Ekardt argues that achieving true sustainability requires systemic changes that extend beyond technological advancements. This includes rethinking human beings’ essential needs, and considering frugality as consumers, redesigning governance systems by embedding sustainability into legal and policy structures and addressing ethical imperatives such as intergenerational justice and global equity (Ekardt, 2020, 2024). Together, these perspectives deepen the understanding of agricultural sustainability as a comprehensive approach whose aim is not only to enhance productivity but also to ensure the protection of ecosystems, to foster social equity, and to support the ethical stewardship of resources. By integrating environmental, economic, social, ethical, and governance dimensions, sustainable agriculture becomes a transformative pathway toward securing long-lasting agrifood systems and livelihoods for farmers while safeguarding the planet's ecological balance for future generations.

2.2 The Importance of Achieving Efficiency in Agriculture

Technical efficiency refers to the ability of farms to achieve the maximum possible output given the resources available. It measures operational performance and identifies whether farms are fully utilizing their inputs, such as labor, land, and machinery, but also sunshine, rainfall and traditional knowledge. Allocative efficiency, on the other hand, evaluates whether the mix of inputs is being utilized in a cost-effective manner, considering their relative prices and marginal productivity (Farrell, 1957). Cost efficiency is an amalgamation of technical and allocative efficiencies, reflecting the overall economic performance of a farm. Scale efficiency examines whether farms are operating at the optimal size to maximize productivity and minimize costs, offering insights into the potential benefits of adjusting operational scale (Charnes et al., 1978). Environmental efficiency considers not only inputs and outputs but also the environmental impacts of farming processes (Fraanje et al., 2019). These efficiency metrics play a crucial role in advancing agricultural sustainability when farmers make deliberate choices to optimize resource use, enhance economic viability and protect ecological resiliency on the farm (De Koeijer et al. 1999, 2002).

Achieving these efficiencies is critical for agricultural sustainability, especially in regions like Western Newfoundland, where environmental and socio-economic challenges require innovative farming strategies. Improvements in efficiency can enhance profitability for farmers, reduce resource wastage, and mitigate environmental impacts, thereby supporting the long-term sustainability of farming systems. Understanding these efficiencies is particularly relevant for informing evidence-based policies and promoting resilient agricultural practices in the face of climate change and resource constraints (Färe et al., 1994).

2.2. The Agricultural Context of Western Newfoundland

The study area, Western Newfoundland, lies in the Newfoundland and Labrador province of Canada. It is part of the boreal ecozone, characterized by acidic soils, rugged terrain, and a harsh climate. The region's boreal climate features cool summers, cold winters, and a short growing season of approximately 3 to 4 months, as well as high annual precipitation, including significant snowfall in winter, which affects soil moisture recharge and drainage (AAFC, 2021). These climatic conditions, combined with frequent freeze-thaw cycles, create challenges for soil health, crop growth, and farm management. As a result, the province experiences the challenges of food insecurity among all Canadian provinces, with 23% of the province's families being food insecure in 2022 (Statistics Canada, 2023). The province has about 400 different farms which produce a limited number of commodities, dairy products, chicken, eggs, greenhouse and nursery produce, vegetables and berries (NL, 2019). In 2019, the food self-sufficiency in the province was assessed to be 10 -12%, and at that time the provincial government set the target to double food self-sufficiency in the province by 2022 (NL, 2018).

3. Research Methodology

3.1 Study Area

The study area is Western Newfoundland (Figure 1), the western region of Newfoundland, the island portion of the Newfoundland and Labrador (NL) province in Atlantic Canada. The region is characterized by podzolic soils (low fertility) and a cool summer, boreal climate that significantly influences its agricultural production. The predominant soils are acidic podzols, often low in nutrients and prone to leaching, requiring amendments for optimal crop growth. Poorly drained gleysols are also common in the area's valleys and wetlands, affecting soil water retention. The region's boreal climate is characterized by arctic summers, freezing winters, and high annual precipitation ranging from 1100 to 1400 mm, with significant snowfall in winter. A short growing season of 90 – 120 days makes timing critical for planting and harvesting. Vegetables and root crops thrive in the region, due to their adaptability to acidic soils and cooler temperatures, though careful management of soil pH, drainage, and nutrient levels is essential. There are 37 farms in the research area, each producing a combination of field and greenhouse vegetables, herbs, berries, fruit, flowers, hey and nursery sod.

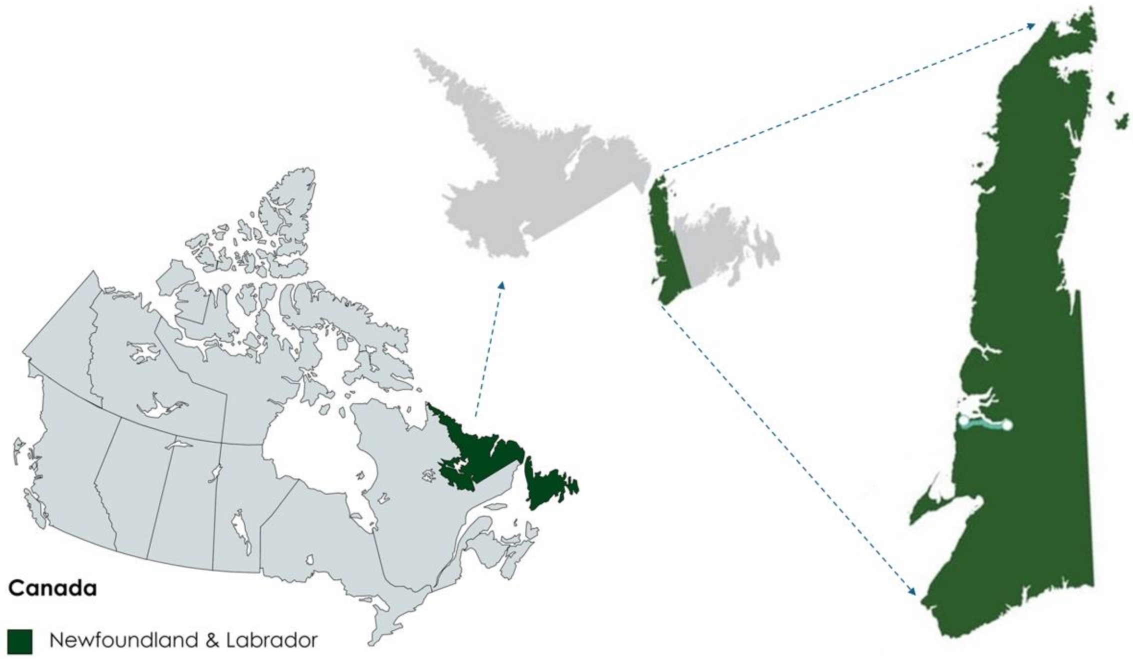

Figure 1: This study area illustrates the geographical location of Western Newfoundland, Canada, highlighting key agricultural areas and the distribution of farms within the region.

3.2 Farm Efficiency as a Measure of Sustainability

Measuring sustainability in agriculture is a difficult task given "the many ways in which crop plants and domestic animals sustain the global human population by providing food and other products" (Harris and Fuller, 2014), and the many ways in which farming activities can be organized to be profitable both to the farmer and to the environment, when conscious management decisions are made by the farmer to protect the diversity and complex functions of the ecological life support system provided by nature (Färe et al., 1994). In this paper, we assume that measuring productive efficiency at the farm level can point to sustainability, as for instance when a farm's productive efficiency is increased with use of less chemical fertilizers and pesticides which normally cause negative environmental impacts.

The farm productive efficiency measurement methods utilized in this study build upon the foundational work of Farrell (1957), which was later advanced by Afriat (1972) and Cooper, and Rhodes (1978), among others. These methodologies were further refined and expanded by Fare, Grosskopf, and Lovell (Färe et al., 1994), who analyzed productivity growth using a non-parametric model, providing the analytical framework for this research. For a detailed introduction to Data Envelopment Analysis (DEA) techniques, readers are encouraged to read Coelli, Rao, and Battese (1998). The current study specifically examines five key efficiency measures: technical, allocative, cost, scale and environmental efficiencies, which are succinctly outlined in the subsequent sections.

3.3 Technical Efficiency

Technical Efficiency (TE) reflects the ability of a farm to maximize its output using a given set of inputs or, conversely, to minimize input usage while maintaining the same level of output. It is a measure of operational performance, indicating how well a farm converts resources such as land, labor, seed, fertilizer, irrigation, and pesticides into agricultural products like yield and residue. TE is evaluated using a non-parametric input-oriented or output-oriented Data Envelopment Analysis (DEA) model, a model which is considered adequate for measuring farm sustainability, under two aspects (environmental and economic) (De Koeijer et al., 2003). In this study, the farms' TE is compared against an "efficiency frontier" formed by the best-performing farms in the dataset. A TE score of 1 signifies that the farm is technically efficient, operating on the production frontier, while a score below 1 indicates inefficiency, with room for improvement through better management practices or adoption of advanced technology. Assessing TE is critical for identifying inefficiencies in resource utilization, enabling targeted interventions to improve productivity and sustainability in farming systems.

The DEA production frontier is constructed using linear programming techniques, resulting in a piecewise linear frontier that "envelops" the observed input and output data. The technologies derived in this way exhibit the standard properties of convexity and strong disposability, as discussed by Fare, Grosskopf, and Lovell (1994). The DEA model is employed to simultaneously construct the production frontier and calculate technical efficiency measures. For the case where data on K inputs and M outputs are available for each of the N farms, the input and output data for the i-th farm are represented by the column vectors $\mathbf{x}_i$ and $\mathbf{y}_i$, respectively. The K × N input matrix X and the M × N output matrix Y represent the input and output data for all N farms in the sample.

3.4 Input-Oriented Model

An input-oriented DEA model minimizes inputs while maintaining the same output levels. We will use the objective function:

$$\min_{\theta} \theta$$

subject to:

$$\begin{gathered} Y\lambda \geq y_0 \\ \theta X\lambda \leq x_0 \\ \lambda \geq 0 \end{gathered} \qquad -------------(1)$$

where:

θ : Technical efficiency score $(0 < \theta \leq 1)$.

X : Input matrix (e.g., land, labor, seed, pesticides and fertilizers etc.).

Y : Output matrix (e.g., yield, residue).

x_0, y_0 : Input and output vectors of the decision-making unit (DMU) being evaluated.

λ : Intensity variables representing the linear combination of peer DMUs.

3.5 **Output-Oriented Model**

An output-oriented DEA model maximizes outputs for a given level of inputs.

We will use the objective function:

$$\max_{\phi} \phi$$

subject to:

$$\begin{aligned} \phi y_0 &\leq Y\lambda \\ X\lambda &\leq x_0 \\ \lambda &\geq 0 \end{aligned} \qquad ------------(2)$$

where, ϕ : Output efficiency score ($\phi \geq 1$).

In this context, θ is a scalar, $N1$ is an $N \times 1$ vector of ones, and λ is an $N \times 1$ vector of constants. The value of θ represents the technical efficiency score for the i-th farm. It will satisfy the condition $\theta \leq 1$, with a value of 1 indicating that the farm lies on the frontier, signifying it is technically efficient according to Farrell's (1957) definition. To obtain the technical efficiency score for each farm in the sample, the linear programming problem must be solved N times, once for each farm.

The DEA problem in equation (1) can be intuitively understood as follows: it takes the i-th farm and attempts to shrink its input vector, x_i, as much as possible, while staying within the feasible input set. The inner boundary of this set is a piecewise linear isoquant (labeled SACDS' in Figure 2), defined by the frontier data points; these are the technical efficient farms in the sample. The process of contracting the input vector x_i produces a projected point, $(X\lambda, Y\lambda)$, that lies on the surface of this technology. This projected point is a linear combination of the observed data points, and the constraints in equation (1) ensure that the projected point remains within the feasible set.

In Figure 2, four farms (A, B, C, and D) are producing the same level of output but using different amounts of two inputs, x_1 and x_2. Farms A, C, and D form the production frontier (or isoquant), as it is not possible for any of these farms to reduce their input usage without falling outside the feasible production set. On the other hand, Farm B is inefficient because it can reduce its input usage to the projected point B', which lies on the frontier. The technical efficiency (TE) of Farm B is represented by the ratio $\frac{0B'}{0B}$, indicating the proportion of input reduction needed for Farm B to become technically efficient.

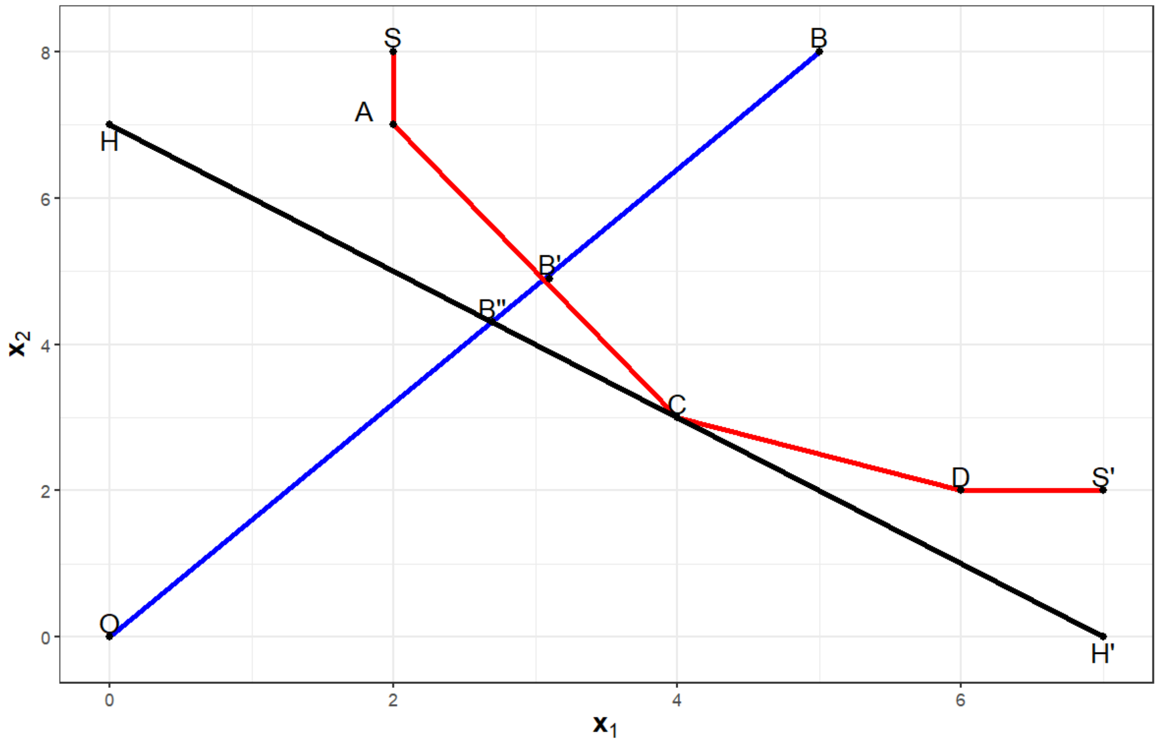

Figure 2: This figure illustrates the concepts of technical and allocative efficiency using a production frontier. The isoquant represents the optimal combination of inputs required to produce a given level of output. Farms operating on the frontier (A, C, and D) are technically efficient, while Farm B, located below the frontier, is inefficient due to excess input use. The allocative efficiency is determined by the isocost line, which identifies the most cost-effective input combination. The distance between Farm B and the frontier indicates the extent of inefficiency, highlighting potential areas for input optimization and cost reduction.

3.6 Allocative Efficiency (AE)

If input price information is available, allocative efficiency can be assessed using the isocost line, HH', which is tangent to the isoquant at point C. If all farms face the same relative prices represented by this line, farm C is producing at the minimum possible cost, while the other farms are not. Even though farms A and D are technically efficient, they are not cost efficient because they are allocatively inefficient. This means they are not using the inputs in the optimal proportions according to the observed input prices, and therefore, they are not producing at the lowest possible cost; Farm B, on the other hand, is both technically and allocatively inefficient. Its allocative efficiency can be calculated by the ratio $\frac{0B''}{0B'}$, while its cost efficiency can be measured by the ratio $\frac{0B''}{0B}$. Cost efficiency is the product of technical efficiency and allocative efficiency, so $\frac{0B''}{0B} = \frac{0B'}{0B} \times \frac{0B''}{0B'}$.

AE measures the ability of a farm to use its resources in an optimal way, given the relative costs of inputs and the desired level of output. Unlike technical efficiency, which focuses solely on physical resource utilization, AE evaluates whether a farm selects the most cost-effective combination of inputs, such as land, labor, seed, fertilizer, irrigation, and pesticides, to minimize production costs or maximize profitability. A farm with a high AE score (close to 1) is effectively minimizing costs for its input mix while achieving its output goals, taking into account prevailing market prices.

AE is calculated using DEA, which incorporates both input prices and observed output levels to determine cost minimization strategies. Understanding AE is crucial for guiding farms toward more economically viable operations, ensuring that resources are allocated efficiently to enhance competitiveness and profitability within the constraints of farms' budget and market dynamics.

The cost and allocative efficiencies are determined by solving the following cost minimization DEA problem:

$$
\begin{aligned}
\text{Minimize} \quad & \lambda, x_i^* \; w_i' x_i^* \\
& -y_i + Y\lambda \geq 0 \\
\text{subject to:} \quad & x_i^* - X\lambda \geq 0 \\
& N1'\lambda = 1, \\
& \lambda \geq 0
\end{aligned}
\qquad ------------(3)
$$

where w_i is the vector of input prices for the i-th farm, and x_i^* (determined by the model) is the cost-minimizing vector of input quantities for the i-th farm, given the input prices w_i and output levels y_i.

The total cost efficiency (CE) for the i-th farm is calculated as:

$$CE = \frac{w_i' x_i^*}{w_i' x_i}$$

where CE represents the ratio of minimum cost$(w_i' x_i^*)$ to observed cost$(w_i' x_i)$ for the i-th farm. Allocative efficiency (AE) is then derived residually as:

$$AE = \frac{CE}{TE}.$$

This approach allows for evaluating how well farms allocate resources to minimize costs, given their technical efficiency levels.

3.7 Scale Efficiency

The DEA models discussed so far are based on the Variable Returns to Scale (VRS) approach. This means that the constructed production frontier can exhibit local properties of increasing, constant, or decreasing returns to scale. Increasing returns to scale occur when output increases by a higher proportion than the increase in inputs used in the productive process. If output increases by less than the proportional increase in inputs, there are decreasing returns to scale. To impose Constant Returns to Scale (CRS) on the DEA problem described in equation (1), the convexity constraint ($N1'\lambda = 1$) is removed. By doing so, the model assumes that all farms operate under constant returns to scale. This adjustment allows for the calculation of the scale efficiency measure, as described in the following sections.

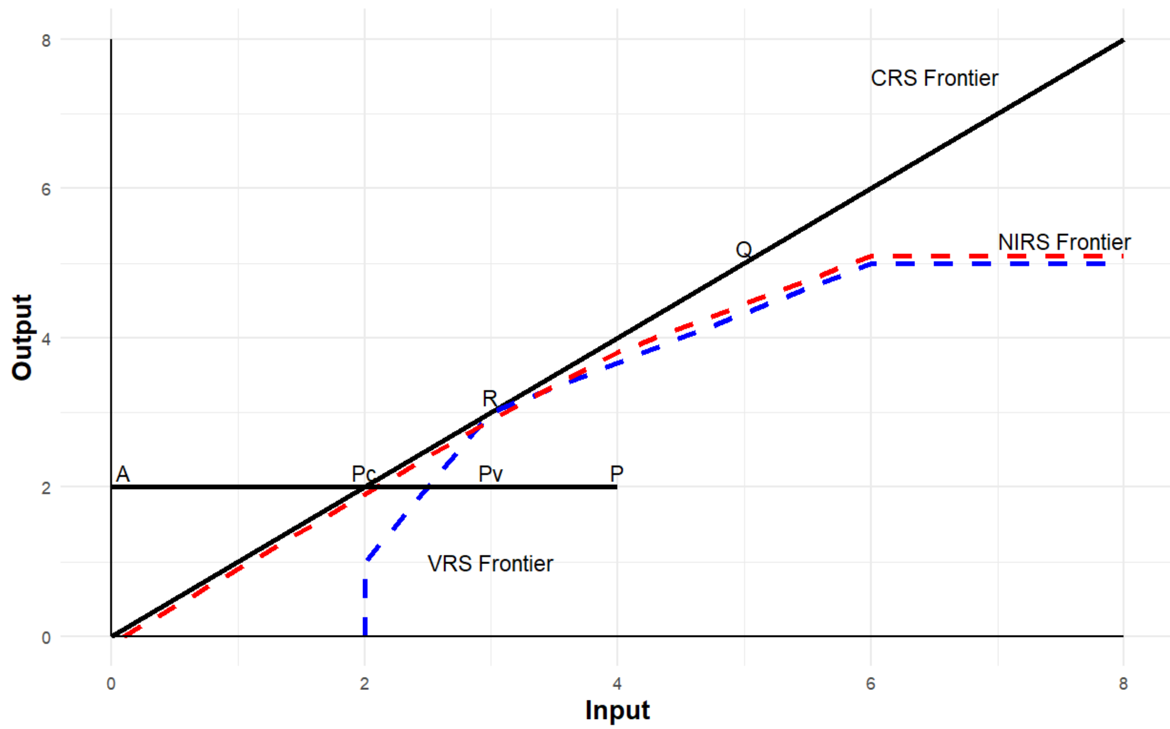

Figure 3: Constant, Increasing, and Decreasing Returns to Scale in Farm Production. The solid straight line represents Constant Returns to Scale (CRS), the dotted red line indicates Non-Increasing Returns to Scale (NIRS), and the dotted blue line depicts Variable Returns to Scale (VRS).

This Figure 3 illustrates how scale efficiency is determined using a simple example with one input (x) and one output (y). The curved line represents the production frontier under Variable Returns to Scale (VRS), capturing variations in efficiency based on farm size. The straight line represents the Constant Returns to Scale (CRS) scenario, where inputs and outputs increase proportionally. Farms operating at the optimal scale (point C) achieve maximum efficiency under CRS. Farms positioned to the left of point C (e.g., point A) experience Increasing Returns to Scale (IRS), meaning a proportional increase in inputs results in a greater than proportional increase in output, suggesting potential benefits from expansion. Conversely, farms to the right of point C (e.g., point D) operate under Decreasing Returns to Scale (DRS), where additional inputs lead to a less than proportional increase in output, indicating inefficiencies that could be mitigated by reducing scale. This figure provides a framework for assessing farm size adjustments to enhance productivity and resource efficiency in agricultural systems.

At point P, the input-oriented technical inefficiency under CRS is represented by the distance PP_C, while under VRS, it is PP_V. The difference between these two inefficiency measures, $P_C P_V$, is due to scale inefficiency. These efficiency measures can be expressed as ratios:

$$\mathrm{TE}_{CRS} = \frac{AP_C}{AP},\ \mathrm{TE}_{VRS} = \frac{AP_V}{AP},\ \mathrm{SE} = \frac{AP_C}{AP_V}$$

All these measures are bounded between 0 and 1. From this, scale efficiency (SE) can be calculated as:

$$SE = \frac{\mathrm{TE}_{CRS}}{\mathrm{TE}_{VRS}}$$

One limitation of this scale efficiency measure is that it does not reveal whether the farm is operating under increasing or decreasing returns to scale. This can be addressed by running another DEA model imposing Non-Increasing Returns to Scale (NIRS). This modification is made by replacing the $N1'\lambda = 1$ constraint in the DEA model with $N1'\lambda \leq 1$.

The NIRS frontier is also shown in Figure 3. To identify the nature of scale inefficiency for a specific farm:

- If the NIRS TE score equals the VRS TE score ($\mathrm{TE}_{NIRS} = \mathrm{TE}_{VRS}$), the farm operates under decreasing returns to scale (DRS).
- If the NIRS TE score is less than the VRS TE score ($\mathrm{TE}_{NIRS} < \mathrm{TE}_{VRS}$), the farm operates under increasing returns to scale (IRS).
- If $\mathrm{TE}_{CRS} = \mathrm{TE}_{VRS}$, the farm is operating under constant returns to scale (CRS).

To understand variations in efficiency scores across farms, these scores were regressed against farm-specific characteristics. A Stepwise regression model was employed to find the factors affecting efficiency (Żogała-Siudem and Jaroszewicz, 2021a). These analyses provide valuable insights into scale inefficiency and its causes, helping identify whether farms can improve their performance by adjusting their scale of operation(Smith, 2018a).

3.8 Environmental Efficiency:

In addition to the traditional measures of farm efficiency, environmental efficiency (EE) is a critical aspect of sustainability. Environmental efficiency helps to assess the ability of a farm to produce its outputs while minimizing environmental impacts, particularly in terms of pollution and resource depletion. Tyteca (1996) highlights that environmental efficiency can be measured by comparing the amount of pollution or environmental damage generated by a farm's activities relative to its output. This concept aligns with the definition of sustainable agriculture, which emphasizes minimizing ecological footprints while maintaining productive capacity.

Further elaborating on environmental efficiency of farms, De Koeijer et al. (2002) presents a model to assess EE in a similar manner to the model for input-saving technical efficiency, except that instead of using the observed inputs, the model uses the environmental impacts associated with these inputs. The environmental efficiency thus indicates the amount of pollution that could be reduced, which from an environmental perspective is more relevant than merely measuring the possible output increase per unit of pollution. By replacing the observed inputs with their calculated environmental impacts, we can obtain a more accurate understanding of how efficiently a farm utilizes resources from an ecological standpoint. This is particularly important for understanding the sustainability of farming systems in the face of growing environmental challenges.

Technical, allocative, cost, scale, and environmental efficiencies all contribute to a more sustainable agricultural system by balancing economic, environmental, and social factors. Technical efficiency ensures that farms use resources optimally, reducing waste and minimizing environmental impacts, thus supporting both economic and ecological sustainability. Allocative efficiency promotes the optimal distribution of resources, ensuring that farms achieve maximum output without overexploiting inputs, contributing to sustainable production practices. Cost efficiency further enhances sustainability by reducing unnecessary expenses and limiting the use of harmful chemicals, thus lowering environmental degradation. Scale efficiency addresses the optimal farm size, ensuring that operations are neither too small (inefficient) nor too large (leading to resource overuse), thus promoting sustainability through better resource management. Finally, environmental efficiency directly targets the reduction of pollution (waste) and resource depletion, making farms more ecologically sustainable. Together, these efficiency models align economic goals with environmental stewardship, helping farmers adopt practices that ensure long-term sustainability of the farm while maintaining its profitability. Improving this set of efficiencies translates into more sustainable farming practices, which are essential for the future of an agrifood system.

3.9 Data Collection

The agricultural study conducted in Western Newfoundland involved contacting all 37 farms in the region during September to November 2024, with 15 farms agreeing to participate. Data collection was achieved through structured questionnaire surveys, focusing on both input and output metrics. Input data encompassed resource usage, including land area, labor, water, fertilizer and pesticide usage, and energy consumption. On the output side, data were gathered on farm productivity and sustainability indicators such as crop yield, economic returns, and environmental indicators, like soil health and carbon emissions, and social indicators including labor conditions and community impact. This structured approach ensured the collected data were both consistent and representative of the farms' operational practices, providing an overview of agricultural sustainability in the region.

3.10 Decision-Making Units (DMUs)

The DMUs in this study are the 15 individual farms surveyed in Western Newfoundland. Each farm as one DMU operates independently, employing various agricultural practices and resource management strategies. The analysis did evaluate the efficiency of these farms by comparing their input usage against output production, providing insights into the effectiveness and sustainability of their operations.

3.11 Implementation of DEA

To evaluate agricultural efficiency and sustainability in Western Newfoundland, a structured DEA was implemented. The analysis employed input-oriented DEA models under both Variable Returns to Scale (VRS) and Constant Returns to Scale (CRS) assumptions, ensuring a comprehensive assessment of farm efficiency. Input and output data were normalized to maintain consistency across datasets, and efficiency scores for each DMU were calculated using the "Benchmark" and "deaR" package in the RStudio integrated development environment (IDE) (Bogetoft et al., 2024; Coll-Serrano et al., 2023). This package streamlined the process by enabling seamless data integration, efficient computation of DEA scores, and application of both VRS and CRS models. It also provided visualization tools to depict efficient frontiers and highlight best-performing farms, allowing for an intuitive understanding of the results. The analysis identified areas of inefficiency and generated actionable insights to enhance farm productivity and sustainability. By incorporating both CRS and VRS approaches, the study offered a holistic understanding of technical and scale efficiencies. This dual approach emphasized resource use optimization and supported the development of sustainable agricultural practices tailored to the specific needs of the region. Additionally, a Stepwise regression model was employed to identify key factors influencing farm efficiency (Żogała-Siudem and Jaroszewicz, 2021). Stepwise regression is a systematic statistical method that iteratively selects or removes predictor variables based on predefined criteria, such as the Akaike Information Criterion (AIC) or p-values, to improve model performance and reduce multicollinearity (Smith, 2018). In this study, stepwise regression was used to determine the most significant socioeconomic and environmental variables affecting technical, allocative, cost, and environmental efficiencies. This approach enabled a more targeted analysis of efficiency determinants, allowing for the identification of critical factors—such as farmer experience, farm size, education level, and environmental practices—that impact overall farm performance. The combination of DEA and stepwise regression provided a robust framework for evaluating agricultural efficiency while offering actionable insights to optimize resource use and enhance sustainability.

4. Results & Discussion

Figure 4 presents the Correlation Heatmap, which is employed to examine the relationships between key agricultural inputs used by the farms (Capital, Land, Labor, Fertilizer, Pesticides, Fuel, Maintenance, Electricity, Seed) and the output (Revenue). By visualizing the Pearson correlation matrix, the heatmap offers an intuitive means to identify the strength and direction of these relationships. The inputs *Fertilizer, Pesticides*, *Labor* and *Fuel* exhibit strong positive correlations with *Revenue*, underscoring their substantial impact on productivity. Moreover, the heatmap highlights interdependencies between inputs, such as the high correlation between *Fertilizer* and *Pesticides*, indicating their combined influence on the outcomes. This visualization simplifies the interpretation of complex numerical relationships, allowing for the identification of key variables driving farms' *Revenue* and a deeper understanding of how the inputs interact. It also aids in making informed decisions regarding resource allocation and optimizing farms' agricultural performance. As a result, the selected input and output indicators for this study align with the assumption of the same direction, enabling the use of the DEA model for analysis.

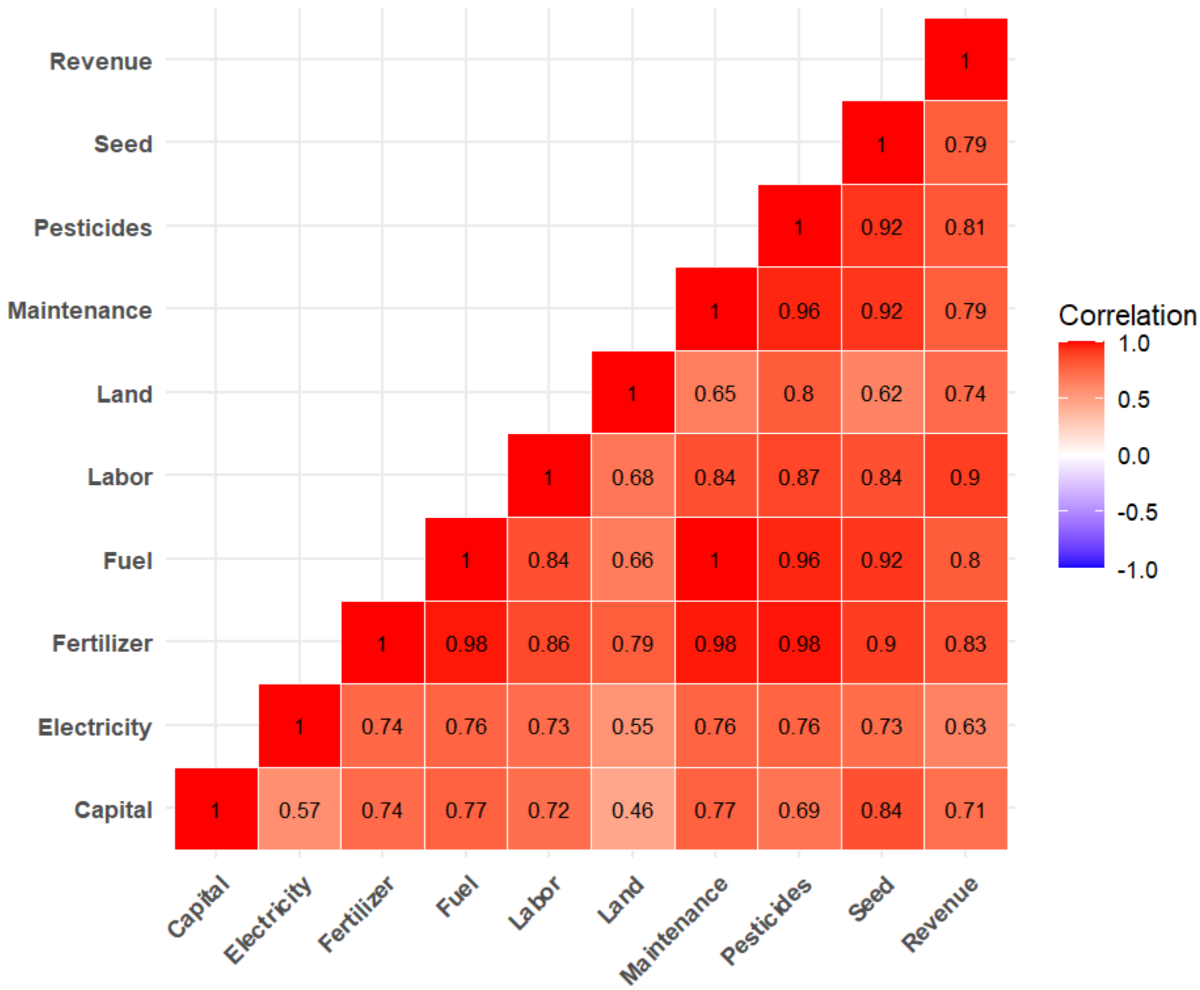

Figure 4: Heatmap of Pearson correlation coefficients between key agricultural inputs (capital, electricity, fertilizer, fuel, Labor, land, maintenance, pesticides, seed, revenue) and the output (revenue).

4.1 Efficiencies

The TE of the 15 decision-making units (DMUs) under the input-oriented DEA model with VRS demonstrate a high level of operational efficiency among most farms. With a mean efficiency score of 0.952 (95.2%), most DMUs are performing near the production frontier. Notably, 12 out of the 15 DMUs (80%) achieved full efficiency (TE = 1), indicating optimal input utilization (Figure 5). The remaining farms showed varying levels of inefficiency, with one DMU operating at a TE of 0.6473 (64.7%) and two others within the range of $0.8 \leq TE < 0.9$ (13.3%). The median and quartile statistics further reinforce the strong performance, as 50% of the DMUs achieved full efficiency, and the first and third quartiles both equaled 1. These results highlight a dominant group of efficiency leaders, while a small subset of farms requires targeted improvements to better align with the efficiency frontier.

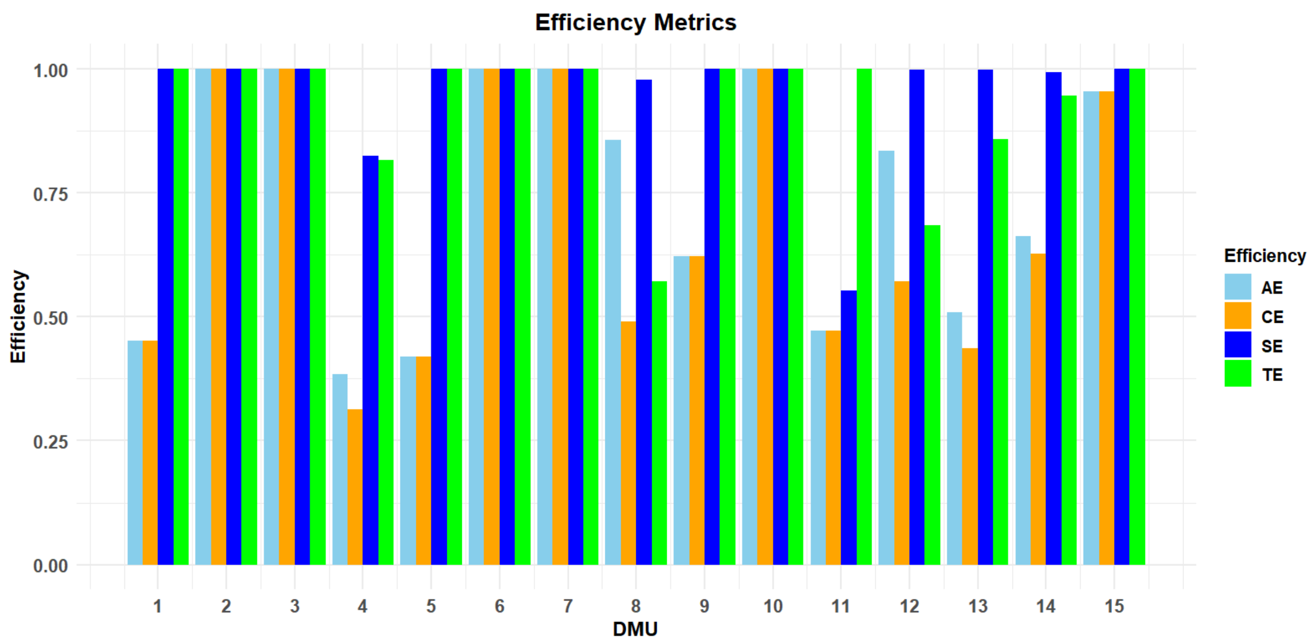

Figure 5: Efficiency metrics of decision-making unit (DMU) shows technical efficiency (TE), cost efficiency (CE), allocative efficiency (AE), and scale efficiency (SE). Efficiency value ranges from 0 to 1.

Figure 5, illustrating the efficiency analysis of the 15 DMUs, reveals significant variations in their performance across TE, CE, AE, and SE. While most DMUs exhibit full technical efficiency (TE = 1), indicating optimal resource utilization, cost and allocative inefficiencies are evident in several cases. DMUs 2, 3, 6, 7, and 10 stand out as fully efficient across all metrics, serving as benchmarks. Conversely, DMU 4 demonstrates the lowest performance, with a CE of 0.31 and AE of 0.38, highlighting significant cost and resource allocation issues. Other DMUs, such as 13 and 5, also exhibit low CE and AE scores, indicating room for improvement in managing costs and resource allocation. Scale inefficiency is most pronounced in DMU 11 (SE = 0.55), suggesting the need for resizing operations. These results emphasize the importance of targeted strategies to address specific inefficiencies in farming operations, such as improving cost management, optimizing input use, and adjusting scale for underperforming DMUs.

4.2 Environmental Efficiency

The environmental efficiency scores provide critical insights into the sustainability of the operations of the 15 DMUs by evaluating their efficiency (Figure 6) in minimizing environmental impact relative to their outputs. The environmental efficiency scores range from a low of 0.2597 (DMU 13) to a perfect 1 (achieved by several DMUs, including 3, 5, 6, and 7), indicating significant variability in the environmental performance of the units. High environmental efficiency scores, such as those of DMU 3, 5, 6, 7 and DMU 10, suggest that these units are managing their resources and production processes sustainably, with minimal environmental degradation. In contrast, DMUs with lower scores, such as DMU 4 (0.2630) and DMU 12 (0.3179), highlight potential areas for improvement, such as optimizing input usage or adopting greener practices. These variations underscore the importance of integrating environmental efficiency considerations into agricultural management practices. The results align with existing literature that emphasizes the role of sustainable resource management in achieving both economic and ecological goals in farming operations (Mehmood and Munawar, 2023; De Koeijer et al. 2002). Future interventions should focus on promoting eco-friendly technologies, efficient resource utilization, and environmental education to enhance the sustainability of operations across all DMUs in the study area.

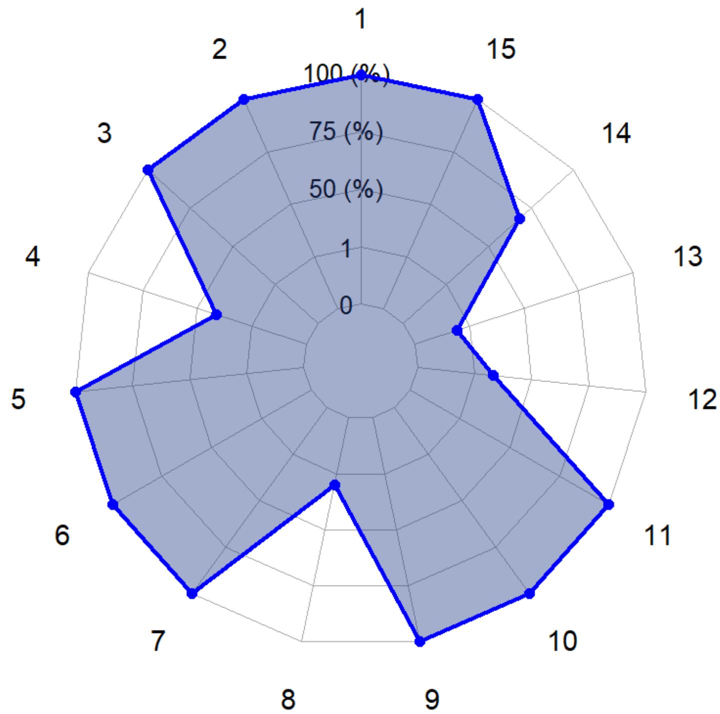

Figure 6: Radar chart illustrating the Environmental Efficiency scores of Decision-Making Units (DMUs).

The summary of the input use ratios farms wise across the 15 DMUs in Figure 7 reveals a pattern of inefficient resource utilization. With a mean input use ratio of 2.10, on average, farms are using more inputs than necessary for cost efficiency. While some DMUs (e.g., DMU 2, 3, 6, 7, and 10) operate at an optimal level with a ratio of 1.00, indicating cost-efficient use of inputs, others exhibit significant resources overuse. For instance, DMU 13 has an input use ratio of 4.31, signaling extreme inefficiency. The median ratio of 1.79 suggests that overuse of inputs is more common than optimal usage, but the overuse is generally moderate. Addressing these inefficiencies could lead to better resource allocation and enhanced farm productivity.

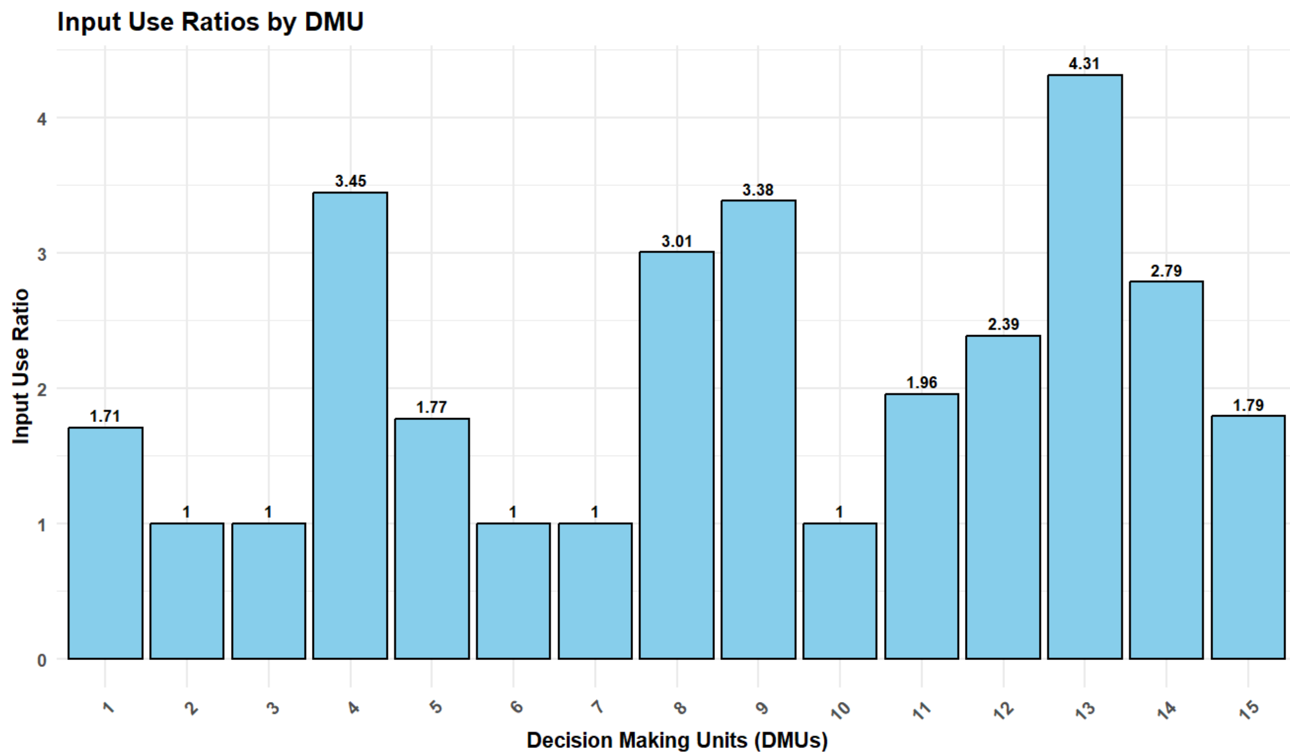

Figure 7: Bar graph depicting input use ratios across the Decision-Making Units (DMUs) in Western Newfoundland , Canada. The chart illustrates varying levels of resource utilization efficiency, with an optimal input use ratio of 1.0 and overuse indicated by ratios greater than 1.

4.3 Factors Explaining Efficiency

The Stepwise regression model reveals that several factors influence the TE of the farms, with significant predictors including *Farmer's Experience* and *Age* and the *Number of years of farm's operation*. Marginal significance was observed for *Female Labor*, while *Drainage* was not a significant predictor in this model. These findings highlight the importance of farmers' *age and experience,* as well as of the *number of years of farm's operation* in determining technical efficiency, but they also suggest that additional factors or model adjustments may be necessary for a more comprehensive understanding of the drivers of farm efficiency.

The stepwise regression model examining the factors influencing environmental efficiency suggests that both *Education* and *Farm Type* significantly affect environmental efficiency, with Education emerging as the stronger predictor. Specifically, *Education* has a positive impact on environmental efficiency (p-value = 0.0208), while *Farm Type* has a marginally significant effect (p-value = 0.0592), indicating that farms with different types of operations may exhibit varying levels of environmental efficiency. However, when controlling for the other factors, the baseline value for environmental efficiency is not significantly different from zero. This model highlights the importance of education and farm type in determining environmental efficiency, but further research may be needed to explore other factors that could contribute to environmental efficiency.

4.4 Case Study

One farm (DMU 3) has embraced sustainable farming practices by implementing no-dig farming methods, permaculture techniques, introducing rainwater harvesting systems, and integrating poultry farming with crop growing operations. Composting and reusing as many natural resources as possible has formed the backbone of the farm's sustainable operation design, promoting efficient resource use and minimizing waste (Owsianiak et al., 2021). The farm raises ducks, turkeys, egg-laying chickens, and is home to an energetic Labrador Retriever, Benelli, contributing to the farm’s dynamic ecosystem (Oldfield et al., 2018). The farm grows a wide variety of crops, providing nourishment for the farmer’s family and promoting self-sufficiency. This farm stands out as a model of efficiency, excelling in all efficiency metrics of this study, and serves as a prime example of a truly sustainable farm (Campanhola and Pandey, 2018).

This farm contributes significantly to environmental sustainability through its holistic and regenerative practices (Todirică et al., 2024). By adopting no-dig farming methods and permaculture techniques, the farm reduces soil disturbance, enhancing soil health, carbon sequestration, and biodiversity. The integration of rainwater harvesting systems ensures efficient water use, conserving this vital resource and mitigating the effects of droughts (Lankford & Orr, 2022). Composting and resource reuse minimize waste, reducing the farm's ecological footprint and fostering a circular economy. The integration of diverse livestock, poultry and crops contribute to a balanced ecosystem, enhancing resilience against pests and diseases without relying on chemical inputs (Stojanovic, 2019). Additionally, the farm's self-sufficiency approach reduces dependence on external resources, lowering greenhouse gas emissions associated with transportation and industrial farming. Altogether, this farm exemplifies sustainable agriculture by restoring environmental health, conserving resources, and contributing effectively to building a resilient agrifood system (Boschiero et al., 2023).

5. Discussion

The analysis in this study offers valuable insights into the agricultural farm's operational performance and sustainability of agricultural practices in Western Newfoundland, Canada, by examining the farms' technical, allocative, cost, scale, and environmental efficiency. This multifaceted approach highlights areas where resource management can be improved and provides benchmarks for high-performing units aiming to be sustainable in the long run and building blocks of sustainable agri-foods systems.

5.1 Efficiency

The study explored the factors influencing agricultural efficiency, noting positive correlations between land, seed, and maintenance costs and efficiency, and negative correlations between efficiency and labor, fertilizer, and fuel costs. These findings align with existing research, which consistently shows that larger land areas and investments in high-quality seeds contribute to efficiency by facilitating economies of scale and improving crop yields (Bournaris et al., 2019). On the other hand, excessive labor usage and inefficient chemical fertilizer and non-renewable fuel consumption are linked to lower efficiency, as they often result in lower use efficiency and resource allocation and environmental damage, as demonstrated by Dube and Guveya (2014) and Galluzzo (2017). The positive effect of maintenance costs on efficiency further supports the importance of proper asset management and equipment upkeep, which are crucial for minimizing downtime and enhancing operational efficiency (Batzios et al., 2022). Additionally, the study observed low variability in efficiency scores, with many farms achieving maximum efficiency. This observation aligns with previous findings by Taoumi and Lahrech (2023), which similarly highlighted that a small proportion of farms operate at peak efficiency, emphasizing the opportunity for broader resource optimization across the agricultural sector.

High environmental efficiency scores reflect the successful integration of sustainable farming practices that maximize output while minimizing environmental impacts. On the other hand, DMUs with lower environmental efficiency scores, indicate inefficiencies in resource utilization, leading to higher environmental burdens relative to their output. These findings align with studies like De Koeijer et al. (2002) and (Leite-Moraes et al., (2023), which emphasize the importance of environmental efficiency in promoting sustainable agricultural systems. The variability in environmental efficiency suggests that while some DMUs are operating sustainably by design, others face challenges related to overuse of inputs, limited access to efficient technologies, or poor resource management. For example, the high environmental efficiency scores of DMUs 3 and 5 demonstrate that achieving both economic and environmental goals is possible, offering sustainability benchmarks for other farming units. Improving the environmental efficiency of underperforming DMUs could involve strategies such as enhancing farmer education on sustainable agro-ecological practices, promoting access to eco-friendly inputs, and implementing policies to incentivize resource conservation. The adoption of precision farming practices could also reduce input wastage and minimize environmental harm, as suggested by Gallardo, (2024).

5.2 Soil & Water Conservation

Healthy soil and water conservation directly affect the technical efficiency of farming operations by influencing nutrient uptake, crop growth, and overall biomass production (Shahbaz *et al*., 2022). Insufficient water limits plant metabolism and reduces yield potential, while excessive water can lead to nutrient leaching, root diseases, and soil structure degradation (Fontes, 2020). Efficient water management practices, such as precision irrigation and rainwater harvesting, ensure that crops receive the right amount of water at the right time, maximizing productivity and resource use efficiency (Forster et al., 2022; Gyimah et al., 2020). Case studies from this research demonstrate that farms employing rainwater harvesting systems and no-dig farming methods achieved significantly higher efficiency scores. By minimizing water wastage and enhancing soil moisture retention, these farms exemplify the benefits of integrating sustainable water management into agricultural practices.

From an environmental perspective, soil and water conservation contributes to sustainability by mitigating the adverse effects of water scarcity and runoff (Ingrao et al., 2023). Practices such as no-dig farming and permaculture improve soil health by enhancing organic matter content and water-holding capacity. This not only reduces reliance on external irrigation sources but also fosters resilience against droughts and erratic rainfall patterns (Ingrao et al., 2023). Environmental efficiency metrics from the study highlight the critical role of water management in achieving sustainability. Farms with efficient water use practices exhibited lower environmental footprints, demonstrating that balancing productivity with ecological conservation is achievable (Hashemi et al., 2024). Moreover, these practices align with global sustainability goals by conserving water resources, protecting soil ecosystems, and reducing greenhouse gas emissions associated with water-intensive farming operations (Saleem et al., 2024).

5.3 Seasonal Soil Water Availability

Seasonal variations in soil water availability significantly impact agricultural efficiency and sustainability (Mukherjee, 2021). During the short growing season in regions like Western Newfoundland, efficient use of available soil water is crucial for maximizing crop yields. Periods of high soil water content following snowmelt or heavy rainfall support rapid growth, but excessive moisture can lead to waterlogging and reduced soil aeration, negatively affecting plant roots and microbial activity (Hannah et al., 2020). Conversely, drier periods during late summer or insufficient moisture retention pose challenges to maintaining productivity. Addressing these seasonal fluctuations requires adaptive practices such as timely crop planting, use of cover crops to enhance water retention, and efficient drainage systems to prevent waterlogging (Grigorieva et al., 2023; Habib-ur-Rahman et al., 2022). By aligning farming practices with seasonal soil water dynamics, farms can optimize resource use, reduce waste, and enhance sustainability in agricultural systems.

5.4 Climate Change Impact on Agricultural Efficiency

Climate change significantly impacts the efficiency metrics assessed in this study—technical, allocative, cost, scale, and environmental efficiency—by altering the foundational conditions of agricultural production. In regions like Western Newfoundland, farmers face challenges from freeze-thaw cycles, fluctuations in growing degree days, and an increase in very hot and wet days, all of which disproportionately affect field crops, particularly potato farming. These climatic shifts disrupt crop growth cycles, reduce soil health, and exacerbate water stress, making it more difficult for farms to optimize input use and achieve technical efficiency. Allocative efficiency is hindered as resource allocation becomes more unpredictable due to the rising costs and variability of critical inputs like water and fertilizers. Cost efficiency is similarly affected by increased expenditures on irrigation systems, climate-resilient crops, and pest control measures required to adapt to these changing conditions. Scale efficiency suffers as smaller farms may struggle to remain viable amidst these pressures, while larger farms face challenges in maintaining consistent outputs. Environmental efficiency is directly impacted as intensified input use and carbon emissions from mechanized and energy-intensive adaptations become necessary. Additionally, King et al. (2020) found evidence of a northern shift in agriculture driven by rising temperatures, further altering regional farming practices and efficiency dynamics. These changes highlight the urgent need for adaptive strategies that enhance efficiency while mitigating the impacts of climate change, ensuring the resilience and sustainability of agricultural systems in the face of these ongoing challenges.

5.5 Government support

Government support plays a crucial role in promoting sustainable farming practices, particularly in improving efficiency and long-term sustainability across the agricultural sector. By offering financial incentives, subsidies, and grants for adopting eco-friendly technologies and sustainable farming techniques, governments can lower the initial investment barriers for farmers (Isabella, 2023). Additionally, policies that promote research and development in sustainable farming practices, such as precision agriculture, water conservation, and soil health improvement, can help farmers access cutting-edge tools and knowledge (Nemade et al., 2023). Providing extension services and training programs is essential for building farmers' capacity to implement resource-efficient practices and adapt to changing environmental conditions. Furthermore, governments can create a favorable regulatory environment that encourages sustainable land management, reduces the overuse of chemical inputs, and incentivizes carbon sequestration practices. By fostering collaboration among farmers, researchers, and policymakers, government support can drive the widespread adoption of practices that not only enhance farm productivity but also safeguard the environment, ensuring the long-term viability of farms and agriculture for future generations (Meemken and Qaim, 2018).

Improving agriculture in the NL province to become more sustainable can be achieved by integrating findings from this study. By focusing on optimizing inputs use—such as organic fertilizers and pesticides, and renewable fuels—farmers can reduce environmental impacts while enhancing productivity. The adoption of advanced technologies like precision farming and eco-friendly practices can address inefficiencies and promote resource conservation (Gawande et al., 2023). Highlighting the role of environmental efficiency, the study underscores the need for balancing increase in productivity with minimal environmental harm, offering actionable insights into efficient land use, better seed quality, and maintenance practices. Supporting farmers through targeted government policies, financial incentives, and educational initiatives can drive the provincial agriculture's transition to sustainability. Such initiatives are already taking place in the province, where since 2021, the federal and the provincial governments have supported the introduction of the Living Lab model, a model aiming to identify and co-develop innovative practices and technologies to mitigate the environmental impacts of agriculture by developing collaboration among farmers, scientists, and other external partners (Reza and Sabau, 2022). This study's localized understanding of NL's unique challenges and opportunities provides a foundation for building a resilient agrifood system that can thrive under both economic and environmental pressures.

6. Limitations and Future Research

One limitation of this study is the reliance on a small sample of available data, which may not fully capture the complexity of agricultural input usage and efficiency across different contexts or geographic regions. The study focuses on a specific set of inputs and outputs, which may not encompass all factors influencing agricultural productivity, such as weather conditions, soil quality, technological advancements, and local market conditions. Additionally, the study assumes that the cost-efficient and technically efficient input levels can be directly compared, which may not always be the case in real-world scenarios where market fluctuations, policy changes, and other external factors can influence input prices and usage. Another limitation is the use of average input use ratios, which may overlook variability and outliers that could provide more nuanced insights. Furthermore, although there are 37 farms in the Western Region of Newfoundland, the data was only collected from 15 farms, which may not be a representative sample of the entire farming community. The data was collected through a questionnaire survey, and the limited sample size could introduce biases or affect the generalizability of the findings.

Future research could explore several avenues to further enhance the sustainability and efficiency of agricultural practices in Newfoundland and Labrador and beyond. One key area of investigation could be the integration of advanced technologies such as precision farming tools, which use data and automation to optimize input use and reduce environmental impacts. Additionally, studying the role of climate change in altering farming practices and the adaptability of different farm systems could provide critical insights into long-term sustainability of NL agriculture industry. Research could also examine the economic and social factors influencing farm efficiency, including access to capital, knowledge, and markets. Investigating the adoption of alternative farming methods, such as agroecology, agroforestry, integrative farming or regenerative agriculture, could also provide valuable comparisons with traditional farming practices. Furthermore, future studies could focus on improving the scalability of sustainable practices by analyzing various sizes farm operations and their feasibility in different regions. Finally, cross-disciplinary research that combines agronomy, economics, and environmental sciences, or transdisciplinary approaches which co-create knowledge by integrating insights from various academic disciplines and social partners could offer a more comprehensive understanding of the factors that contribute to agricultural sustainability and resilience in the face of evolving environmental and market conditions.

7. Conclusion

This study provides an assessment of agricultural sustainability in the Canadian province of Newfoundland and Labrador (NL), by focusing on the technical, allocative, cost, and environmental efficiency of a sample of farms located in Western Newfoundland. The findings demonstrate that most farms operate with high technical efficiency, highlighting their effective use of available resources. However, disparities in the cost, allocative, scale and environmental efficiency reveal significant room for improvement, particularly in optimizing input utilization and minimizing environmental impacts. Factors such as excessive chemical fertilizer overuse, and suboptimal scaling were identified as key contributors to inefficiency, while land optimization, quality seed use, and regular maintenance emerged as drivers of enhanced productivity and efficiency. Similarly, the integration of environmental efficiency metrics into the analysis underscores the importance of balancing economic performance with environmental sustainability in agriculture, a social-ecological system which thrives on the life sustaining ecological services available in nature. High-performing farms can serve as benchmarks for implementing sustainable farming practices, such as precision farming, targeted input application, and resource conservation, while underperforming farms can highlight areas for targeted interventions. The study emphasizes the potential of advanced technologies, government support, and farmer education in promoting sustainable practices and in reducing the environmental footprint of farming operations.

Localized insights from NL's unique agricultural context provide actionable strategies for addressing region-specific challenges, such as small-scale operations and resource constraints. By identifying inefficient farms, agricultural extension specialists can implement targeted interventions to enhance efficiency and promote sustainability. Policymakers can leverage these findings to tailor policies that encourage sustainable farming practices and improve farm efficiency. Furthermore, the study identifies opportunities for further research, including the role of climate change, adoption of alternative farming methods, and integration of advanced technologies to enhance farming resilience. By bridging the gap between efficiency and sustainability, this study lays the groundwork for developing a resilient agrifood system in the NL province. It highlights the critical need for collaboration among farmers, researchers, and policymakers to foster innovative thinking in efficient use of resources and ensure long-term agricultural sustainability in the face of evolving environmental and economic challenges.

CRediT authorship contribution statement

KI: Conceptualization, Methodology, Formal Analysis, Data Curation, Visualization, Writing—Original Draft. GS: Conceptualization, Methodology, Supervision, Validation, Writing—Review and Editing. JD: Validation, Methodology, Supervision, Writing—Review and Editing. MC: Validation, Supervision, Writing—Review and Editing, JD: Validation, Writing—Review and Editing. LG: Validation, Methodology, Supervision, Project administration, Funding acquisition, Writing—Review and Editing.

Declaration of competing interest

The authors declare that they have no affiliations with or involvement in any organization or entity with financial interest in the subject matter or materials discussed in this manuscript.

Data availability

All data that support the findings of this study are included within the article.

Ethical compliance

This research received ethical approval from the Grenfell Campus Research Ethics Board (GC-REB) due to the involvement of human participants.

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