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Original Paper

Emissions and Efficiency Outcomes of Variable Rate Fertilizer Application: A Case Study of Canola Yield and Sustainability

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***Abstract*—Agriculture contributes significantly to greenhouse gas emissions, mainly attributable to the ineffective and uniform application of fertilizers, seeds, pesticides, and irrigation water. Precision agriculture technologies, especially those utilizing variable rate input applications, provide an effective solution by modulating input quantities according to the distinct conditions of each field segment. While prior research has examined the theoretical advantages of these technologies, few empirical studies have measured environmental and agronomic effects across various input types. This study examines primary data from variable rate fertilizer application by quantifying the reductions in input utilization and corresponding scope three greenhouse gas emissions. The analysis contrasts traditional uniform application methods with precision-based strategies, demonstrating quantifiable advantages in reduced indirect emissions, enhanced input-use efficiency, and improved crop yield. The results encourage precision agriculture techniques by underscoring the environmental and productivity advantages of precision-managed inputs to guide agricultural policy, promote sustainable farming practices, and aid global warming mitigation efforts.**

***Keywords*—agriculture, emissions, precision, sustainability, technology**

I. INTRODUCTION

Agricultural practices account for approximately 10 percent of Canada's total greenhouse gas emissions [1, 2]. These emissions predominantly stem from the extensive application of fertilizers, seeds, pesticides, and irrigation water [1, 2]. Agricultural methods have depended on uniform input applications that overlook the variability in soil, crop health, and nutritional requirements particular to each field [3, 4]. Along with increasing input expenses for producers, uniform application also contributes to environmental problems, including nutrient runoff, eutrophication, pollution from greenhouse gases, and biodiversity devastation [3, 4].

Due to these environmental and economic problems, precision agriculture tools such as Variable Rate Technology (VRT) are gaining attention. VRT tailors the inputs based on the specific needs of the field, using the most recent data gathered from crop and soil conditions. This enables producers to match input rates to the present conditions in the field [5]. VRT is used to reduce unnecessary input use. It can reduce excessive resources, lower input costs, and even reduce the indirect emissions from producing and applying such inputs [3, 6]. By using fertilizer, seed, water, and pesticides more efficiently, VRT can help to improve yields while supporting environmental sustainability through reduced resource consumption.

Although theoretical case studies provide robust support for VRT [5], extensive empirical evaluations assessing the direct environmental and agronomic advantages are limited [7]. This study makes use of primary field data on Variable Rate Fertilizer Application (VRFA) gathered at Steckler Farm, Olds College in Alberta, Canada. The input category was chosen just because of its considerable impact on agricultural emissions and input expenses [3, 8]. The utilization of fertilizers makes up a large share of agriculture's emissions, which are attributable to energy-intensive production methods [3].

This study quantitatively assesses reductions in indirect emissions and resource use efficiency achieved through the implementation of VRFA, utilizing regional analysis and statistical comparisons. The study demonstrates the advantages of VRFA over traditional uniform application methods by comparing emissions reduction, increased input-use efficiency, and higher yields. The study provides insights into the practical benefits and wider ramifications of implementing VRFA methods.

Although the comparison in this study focuses on 2021 and 2024, the field did not move directly from one management system to the other. In the seasons between these two years, the same land was used to grow corn under a variable-rate fertilizer application. Those intermediate years matter as they shaped the baseline from which the 2024 canola crop responded. A field, managed with VRT for multiple seasons, responds differently: nutrient patterns settle, the extremes of fertility begin to soften, and the soil becomes more predictable [9, 10]. Acknowledging this history allows the reader to understand that the 2024 season is not an isolated event but part of a longer trajectory of adaptation, learning, and gradual change within the field.

This paper provides agricultural policymakers and producers with insights for data-driven adoption of precision agriculture practices. In the context of global warming and resource scarcity, such adoption is essential for accomplishing the dual objectives of increasing agricultural output and attaining environmental sustainability.

II. LITERATURE REVIEW

A. *Introduction*

Improving resource efficiency in agriculture has historically been a primary concern for researchers [11]. Enhancing sustainability throughout the agricultural chain is essential for mitigating global food insecurity [12]. Increasingly frequent extreme weather events, including droughts and floods, negatively impact agricultural productivity and exacerbate vulnerabilities within food systems [13]. Existing inefficiencies in agricultural practices worsen these risks and threaten the stability of the food supply [14].

Current agricultural methods may present environmental and economic hazards, such as soil degradation, reduced long-term production, and the excessive application of agricultural inputs beyond the needs of crops and soil [13]. These inefficiencies result in increased production costs and inflated market prices for food commodities [15].

Addressing the challenges requires a shift towards methods that improve production while reducing resource use and negative environmental impacts. Precision agriculture tools, especially VRT, offer a way forward. VRT improves the application of the inputs, helping boost productivity, reduce yield variation, and lower operating costs compared to traditional systems. VRT also promotes environmental sustainability by enhancing soil carbon retention, decreasing nitrogen application, minimizing fuel usage, and reducing tillage [3].

VRT functions in precision agriculture by customizing the application of fertilizers, herbicides, water, and other inputs according to the specific variability of each field [3]. It regulates input rates according to soil properties, topography, meteorological conditions, and several agronomic parameters, thus enhancing resource utilization efficiency and production potential while minimizing environmental repercussions [16]. VRT systems are generally classified into map-based and sensor-based methodologies [17]. Map-based VRT systems depend on prescription maps generated from soil sampling, laboratory analysis, geospatial data, and remote sensing inputs, which determine application rates specific to each zone [4]. Prescription maps are transferred to applicators equipped with accurate positioning devices to direct input distribution [17]. On the other hand, sensor-based VRT requires neither preliminary mapping nor laboratory analysis. Real-time sensor measurements control application rates during field operations, and the gathered data can then be utilized to create prescription maps for future applications [17].

However, there are still relatively few studies that examine the impacts of VRT in practice, particularly its effects on greenhouse gas emissions and resource-use efficiency [3]. The literature review consolidates existing knowledge on VRT and associated precision agriculture methodologies, including variable-rate seeding and irrigation, focusing on global warming mitigation and agricultural sustainability. The review evaluates theoretical frameworks, empirical findings, and practical applications to identify existing evidence and highlight research gaps.

VRT appears as a promising approach to address economic and environmental issues in agriculture [3]. Empirical research should quantify its advantages, enhance acceptance, and guide policy and investment choices. The following sections provide context on VRT, establishing a basis for the evaluation of effects on productivity, resource efficiency, and emissions in agricultural systems.

B. *Environmental Impact of Agriculture*

The extensive dependence on nitrogen-based fertilizers, essential to agricultural systems, has led to considerable nitrogen pollution impacting terrestrial and aquatic ecosystems [4]. Nitrogen runoff from agricultural land exacerbates eutrophication in aquatic ecosystems, resulting in oxygen depletion and a decline in biodiversity [19]. Excessive nitrogen application also increases nitrous oxide emissions, a powerful greenhouse gas with a global warming potential roughly 300 times that of carbon dioxide [3]. Simultaneously, indiscriminate pesticide application undermines ecosystem equilibrium, affects beneficial species, and contaminates soil and water resources [19].

Most agricultural emissions arise from crop production and livestock, not just fertilizer manufacturing or fossil fuel use [1]. Emissions from farm machinery and land-use changes also add to the sector's environmental impact [2]. These gases stay in the atmosphere for a long time, which makes early and continued mitigation necessary [1, 2].

Agriculture needs to become more sustainable, balancing productivity with responsible environmental management [3]. Agriculture's impact on global warming, biodiversity decline, and the disruption of global biogeochemical cycles indicates that it is advancing several planetary boundaries into critical limits [11]. Transformative innovation in agricultural techniques is vital for safeguarding ecological resilience and ensuring long-term stability in food systems.

C. *Variable Rate Technologies Evolution and Potential*

VRT is a key development in precision agriculture that allows inputs to be applied more precisely across a field [19]. It uses data on soil conditions, crop needs, and environmental factors to adjust input rates by zone. This reduces waste, improves input use, and lowers environmental impacts [19]. Improvements in sensors, GPS, and data analysis have made VRT more accurate and practical by enabling real-time assessment of soil, crop, and weather conditions [3, 20].

VRT is made up of several site-specific practices that together support more sustainable agricultural systems [19]. VRFA plays a central role by matching fertilizer application to soil nutrient levels and crop requirements. This approach limits unnecessary fertilizer use, reduces runoff, and lowers environmental impacts without compromising crop nutrition [3, 4]. VRI manages water more carefully by adjusting irrigation based on soil moisture, crop demand, and weather conditions, preventing over-irrigation and related issues such as nutrient leaching and soil degradation, especially in water-limited regions [3, 21]. VRS modifies seeding rates according to soil properties and field variability, leading to more uniform crop stands, less seed waste, and better yield potential [3, 22]. VRPA focuses pesticide application only on areas where pests are present, reducing overall chemical use and protecting beneficial species and surrounding ecosystems [3, 19].

VRT is widely recognized for improving crop production, reducing input costs, and lowering environmental impacts [19]. Early versions depend on basic soil maps and manual adjustments, which restricts precision. Advances in GPS, remote sensing, geospatial modelling, and machine learning have greatly improved accuracy and efficiency [17, 18]. Current VRT systems combine data from soil sensors, yield monitors, and climate tools to support real-time decisions, cut waste, and improve environmental outcomes [4].

Precision agriculture research is aimed at reducing resource use, limiting environmental damage, and improving yield and crop quality. This growing body of work highlights the increasing interest in VRT across a wide range of agricultural systems [20, 23].

D. *Economic and Environmental Benefits*

VRT offers both economic and environmental benefits, making it a useful tool for supporting sustainable agriculture and protecting ecosystems [6].

From an economic perspective, VRT improves input efficiency by applying fertilizers, pesticides, and irrigation water only where and when they are needed. This reduces waste and lowers production costs. As a result, studies report cost savings and higher profit margins, particularly in large-scale farming systems [6]. However, adopting VRT requires financial commitment, time to learn the technology, and some operational risk. Its economic performance depends on factors such as field size, crop type, and the specific technology used [7]. Profitability also depends heavily on access to accurate, site-specific data, which highlights the importance of continued investment in agricultural data and information systems. Long-term, publicly financed research programs are crucial for producing the data required to improve VRT accessibility and acceptance [24].

VRT also offers clear environmental benefits. By reducing the overuse of inputs, it limits nutrient runoff and chemical pollution in bodies of water, which protects aquatic ecosystems and maintains water quality [19]. More precise fertilizer use lowers nitrous oxide emissions, while better irrigation management and targeted pesticide application reduce carbon dioxide emissions by cutting down energy use and input production [3]. In addition, VRT supports soil health by reducing erosion and improving soil carbon retention, which helps maintain long-term productivity and strengthens resilience to climate variability. Healthier soils function as carbon sinks, and VRT aids in global warming mitigation [3] and can diminish nitrate leaching and groundwater pollution [4].

While VRT is not a universal solution, it requires balancing short-term financial investment with long-term environmental gains. The upfront cost, the need for technical skills, and uncertainty around outcomes can slow adoption, especially for smaller producers or those with limited resources [24]. The success of VRT also depends on the type of technology used, the quality of data available, and how well the system is managed. Even with clear benefits, challenges such as skill gaps and unclear returns on investment continue to limit wider adoption [18]. Confronting these obstacles is essential for fostering resource-efficient and environmentally sustainable agriculture.

E. *Efficacy of Technology*

Empirical studies highlight the economic and environmental advantages of VRT across various regions and agricultural systems, enhancing input efficiency, sustaining or increasing crop yields, and improving profitability while minimizing environmental impacts [3, 6, 19]. Research conducted in Virginia-United States, indicated a reduction of approximately 27 kilograms/hectare in nitrogen application using VRT, while maintaining yields comparable to conventional practices, suggesting improved nutrient-use efficiency and enhanced environmental performance [3].

Case studies throughout Europe substantiate the technology's potential. In Greece, VRT achieved a 38 percent reduction in nitrogen application alongside just over 2 percent increase in yields [6]. In the Czech Republic, a study reported yield increases of about 2 percent across all test plots, alongside decreased input usage and enhanced economic returns [6]. The latter study recorded significant reductions in residual soil nitrate after harvest, thereby decreasing the risk of nitrate leaching and groundwater contamination. While many studies show that VRT can improve economic returns and protect soil and water resources [6], the evidence also shows that precision agriculture has strong potential to reduce input use while maintaining or improving productivity [20].

VRT applications in vineyards and pear orchards resulted in water savings ranging from 20 to 50 percent and a decrease in emissions related to global warming [19]. In another study, VRT achieved a 60 percent reduction in fertilizer use and an 80 percent reduction in pesticide use, concurrently increasing yields by 62 percent [19]. The results demonstrate VRT's adaptability to various crop types and growing conditions, along with its ability to conserve water, decrease agrochemical usage, and enhance productivity. The development of precision viticulture as a unique field of research and practice highlights the increasing importance of site-specific management in specialized cropping systems [20].

Research consistently demonstrates that VRT offers clear economic advantages, such as decreased production costs and enhanced profit margins [6]. Alongside environmental benefits, VRT offers a viable option for the agricultural industry to reconcile profitability with long-term sustainability objectives [19].

F. *Best Practices and Challenges in Variable Rate Technology Adoption*

The benefits of VRT are well documented and using it effectively depends on following best practices and strong collaboration between producers, technology providers, researchers, and policymakers [3, 19].

Effective VRT systems depend on good-quality data collection and analysis, since data resolution and accuracy directly affect how well the system performs. Research shows that technologies with higher spatial resolution work especially well in fields with high variability, helping improve yield potential and nitrogen-use efficiency [4]. Selecting the right VRT tools and integrating them into existing farm operations requires careful consideration of crop type, field size, available resources, and specific environmental constraints [7].

Capacity building and knowledge transfer are critical elements in the adoption of VRT. It is essential for stakeholders to receive training in equipment operation, data interpretation, and informed input-management decision-making [25]. Management training is essential, highlighting the importance of ongoing professional development to ensure sustained success in VRT [26]. Agricultural cooperatives, extension programs, and agricultural networks facilitate knowledge exchange and promote best practices, thereby bridging skill gaps and accelerating adoption [17].

Supportive policy frameworks and financial incentives are essential for promoting the adoption of VRT. Measures can include technology subsidies, tax incentives for sustainable practices, and regulatory programs that support environmental stewardship [27]. Public investment in research, innovation, and extension services also plays a key role by improving knowledge sharing and building capacity among producers. Policies such as the European Union's Common Agricultural Policy [28] and the Farm to Fork Strategy [29] exemplify how coordinated policy frameworks can support sustainable production and encourage the adoption of technologies like VRT [3, 19].

Despite these benefits, the adoption of VRT is limited by various challenges. Initial investment, the requirement for specialized expertise, and the intricacies of VRT systems may discourage, particularly small-scale producers [30]. Technical and economic barriers underscore the need for targeted support mechanisms to enhance adoption [26]. Furthermore, perceived risks and uncertainties related to return on investment persist in constraining adoption [18]. Addressing these challenges requires collaboration among stakeholders to build capacity, reduce financial barriers, and establish the long-term benefits of adopting VRT.

G. Summary

VRT represents a progression towards enhancing sustainability and resilience in agriculture [20]. VRT enables accurate and efficient input applications, thereby minimizing the environmental impact of agriculture and enhancing economic outcomes. Empirical studies indicate its ability to reduce emissions, conserve resources, and improve productivity in various production systems [3].

The future of VRT will likely depend on continued technological progress and stronger collaboration across the industry. New tools such as artificial intelligence and machine learning can improve VRT by enabling more adaptive and real-time input management [31, 32]. Combining VRT with other sustainable practices, such as cover cropping and conservation tillage, may further improve carbon reduction and overall environmental performance [33]. Furthermore, increasing access to affordable and accessible VRT systems may be crucial for promoting adoption among small-scale and resource-limited producers [30].

Policy support is essential for facilitating VRT adoption and promoting agricultural transformation. Financial incentives, research funding, and targeted extension programs reduce economic barriers and support investment in VRT [22]. Regulatory frameworks that promote environmental stewardship and encourage sustainable production practices can also support wider adoption of VRT [25]. As agricultural risks continue to increase due to global warming, proactive policy actions are needed to improve system resilience and help producers adapt [34]. By improving input efficiency and lowering environmental impacts, VRT plays an important role in reducing climate-related risks and supporting long-term agricultural sustainability [3].

Building a sustainable and resilient agrifood system requires coordinated efforts across the entire industry. Collaboration among producers, technology providers, policymakers, and researchers is essential for developing practical solutions and strengthening capacity building [25]. Broader access to affordable VRT technologies, along with proper training and technical support, is needed to ensure their effective use [30]. Integrating VRT into sustainable farming practices can help address food production challenges while protecting environmental resources for future generations [30].

III. METHODOLOGY

A. Introduction

This study utilized a comparative, longitudinal field experiment to assess the agronomic and environmental impacts of VRFA compared to uniform fertilizer application in a commercial canola production system.

B. Study Area and Field Trials

The research was conducted at Steckler Farm, part of the Olds College Smart Farm infrastructure located in Central Alberta-Canada (51.65°N, 114.25°W). The field spans approximately 310 acres and presents a heterogeneous landscape with moderate topographical undulation, variable soil texture, and distinct management zones. Classified under the Chernozemic soil order [35], the site offers variable fertility and moisture retention capacities, making it a suitable environment for testing precision agriculture technologies under actual field conditions [36].

Steckler Farm had not been previously subjected to formal precision agriculture field trials prior to the 2021 season. This temporal baseline provided a unique opportunity to compare traditional input strategies with variable rate approaches across consecutive cropping seasons [37]. The site is located within the agroecological transition zone between dark brown and black soil groups, representing a typical prairie cropping system. Weather patterns in the region are continental, with moderate rainfall and large diurnal temperature ranges during the growing season, typically from May through September [38].

Between the 2021 canola season and the 2024 trial, the field was sown with corn twice, and both seasons followed a variable rate fertilizer strategy. These years form an important bridge in the evolution of the site. By the time the 2024 season began, the field had already gone through two cycles of spatially responsive fertilizer use. This continuity is relevant because the performance of the 2024 canola crop reflects not only the decisions made in that year but also the accumulated effects of learning, correction, and stabilization that took place in the intervening seasons [9].

C. Data Sources

Field trial data were collected during the 2021 and 2024 growing seasons, both sown with canola (Brassica napus). In 2021, a uniform fertilizer strategy was implemented using the InVigor Choice LR344PC hybrid [39], while in 2024, a VRFA strategy was employed using the DEKALB 902TF hybrid [40]. All primary agronomic data, including fertilizer application maps, seed placement, and yield monitor outputs, were collected using GPS-enabled equipment and provided by Olds College. Prescription maps for 2024 were generated through site-specific soil sampling and analysis conducted in collaboration with crop input advisors.

Daily weather data for both years, 2021 and 2024, were obtained from a FarmersEdge weather station situated at the north end of Steckler Field. Supplemental climatic data were sourced from Alberta's Agricultural Climate Information Service - ACIS, specifically the Olds College AGDM and Nier AGDM stations [41]. These datasets provided daily measures of precipitation, temperature, and Growing Degree Days (GDD). Observations from field staff and agronomists highlighted that the timing and frequency of precipitation events played a more pivotal role in crop response than total seasonal rainfall. Additionally, residual soil moisture carried over from the preceding years may have contributed to crop performance in both trial seasons.

D. Experimental Design

The field trials conducted in the 2021 and 2024 growing seasons utilized contrasting management strategies to evaluate the effectiveness of VRFA. In 2021, the field received a conventional uniform fertilizer application strategy using the canola hybrid InVigor Choice LR344PC. This uniform rate was determined by the crop advisors and the researchers after taking the soil and climatic factors into consideration. Conversely, in 2024, a spatially optimized VRFA strategy was implemented using the hybrid DEKALB 902TF. Spatial prescriptions were informed by detailed zone-specific soil sampling, historical yield potential mapping, and satellite-based NDVI data, guiding nutrient inputs tailored to soil productivity potential.

E. Measurement Parameters

Key measurement parameters collected during the primary VRFA trials at Steckler Farm included spatially explicit fertilizer application rates of kilograms per hectare (kg/ha), individual nutrient application rates for nitrogen (N), phosphorus (P), potassium (K), and sulfur (S), as well as grain yield bushels per acre (bu/ac). All inputs were tracked using GPS-enabled machinery. The application files were analyzed at the management zone level to evaluate differences in total nutrient use and estimated carbon emissions based on kilograms of carbon dioxide equivalent per hectare (kg CO_2-eq/ha). Grain yield was measured using an on-combine yield monitoring system operating at 1-second intervals, which provided a georeferenced yield map at high spatial resolution. These datasets formed the basis for a comparative analysis of agronomic efficiency under uniform and variable rate strategies.

The embodied energy based on megajoules per hectare (MJ/ha) and lifecycle carbon emissions (kg CO_2-eq/ha) were estimated using coefficients from peer-reviewed literature. Meteorological parameters such as cumulative rainfall, precipitation timing, mean daily temperature, and GDD were used to contextualize the observed agronomic responses. Field-level observations during both growing seasons emphasized that rainfall timing, particularly during key growth stages, had an influence on nutrient uptake and crop development than total precipitation volume. In addition, residual soil moisture from previous seasons was noted as a contributing factor to early-season crop vigor and nutrient availability.

F. Analytical Techniques

To assess the agronomic and environmental impacts of VRFA, this study compared two production years, 2021 and 2024, conducted on a canola field in Alberta-Canada. The 2021 season employed a conventional uniform application strategy, while the 2024 trial utilized spatially optimized VRT. Fertilizer application rates for nitrogen (N), diphosphorus pentoxide (P_2O_5), potassium oxide (K_2O), and sulfur (S), along with corresponding yield and GPS-based spatial coordinates, were recorded using precision agriculture equipment. The goal was to quantify differences in nutrient use, yield performance, GHG emissions, and upstream energy consumption between the two approaches.

Statistical data processing was conducted using RStudio, where raw datasets exceeding one million data points were cleaned, structured, and analyzed. Cleaning procedures included removal of missing entries, identification of outliers using the interquartile range method, and standardization of spatial formats using the *sf* and *dplyr* packages. A 30 square meter grid was applied to the field boundary, and average input and output values were calculated for each cell. This enabled spatially explicit comparisons of fertilizer application and yield across both years.

To account for varietal differences, yield normalization was conducted. The 2021 and 2024 trials used different canola hybrids, specifically InVigor Choice LR344PC and DEKALB 902TF. The normalized yield was calculated using a benchmark for canola, as reported by the Agriculture Financial Services Corporation [42], where the average is 2,455 pounds (lbs) per acre, equivalent to 49.1 bushels per acre. All yield values were converted using the following expression:

$$\text{Yield (bu/ac)} = \text{Yield (lbs/ac)} \div 49.1$$

Fertilizer application rates, originally recorded in pounds per acre, were converted to kilograms per hectare to align with life cycle assessment protocols. The conversion factor used was:

$$1\ \text{lb/ac} = 1.12085\ \text{kg/ha}$$

Embodied GHG emissions were calculated by multiplying the application rate for each nutrient by its corresponding emission factor. These factors account for the upstream emissions associated with raw material extraction, synthesis, packaging, and transport. The calculation was conducted as follows:

$$GHG\_embodied = Fertilizer\ Rate\ (kg/ha) \times Emission\ Factor\ (kg\ CO_2\text{-}eq/kg)$$

The emission factors used in the study are listed below:

- Nitrogen (N): 3.51 kg CO_2-eq/kg [43]
- Phosphorus (P_2O_5): 1.011 kg CO_2-eq/kg [44]
- Potassium (K_2O): 0.576 kg CO_2-eq/kg [44]
- Sulfur (S): 3.35 kg CO_2-eq/kg [44]

To estimate embodied energy use, fertilizer application rates were multiplied by nutrient-specific energy coefficients and adjusted using a land area conversion factor. The formula applied was:

$$Energy\ embodied = Fertilizer\ Rate\ (lb/ac) \times Energy\ Coefficient\ (MJ/lb) \times 2.47105$$

The factor 2.47105 accounts for conversion from acres to hectares. Energy coefficients were drawn from peer-reviewed life cycle inventory studies:

- Nitrogen: 27.5 MJ/lb [8]
- Phosphorus: 5.04 MJ/lb [8]
- Potassium: 3.04 MJ/lb [8]
- Sulfur: 19.05 MJ/lb [45]

Finally, Welch's two-sample t-test was applied to determine whether mean nutrient rates and yields differ significantly between the uniform and variable rate applications. This method was selected for its suitability in samples with unequal variances and different sample sizes. The test was performed on the grid-aggregated data, and the t-statistics were calculated using:

$$t = (\bar{X}_1 - \bar{X}_2) / \sqrt{((s_1^2/n_1) + (s_2^2/n_2))}$$

All statistical analysis were conducted in RStudio at a 95 percent confidence level ($p < 0.05$). The approach used in this study aligns with protocols for spatial agronomic evaluation found in site-specific nutrient management research conducted in Revere, Minnesota [46].

IV. RESULTS

The implementation of VRFA resulted in notable agronomic and environmental enhancements relative to uniform application practices. The comparison employed data from two growing seasons, 2021 (uniform) and 2024 (variable rate), on the same field (51.65°N, 114.25°W), with each year featuring a distinct canola hybrid. InVigor Choice LR344PC was cultivated in 2021, while DEKALB 902TF was sown in 2024.

Average yield increased from 31.7 bu/ac in 2021 to 56.5 bu/ac in 2024, marking a 78.4 percent improvement (see Figure 1 and Table I).

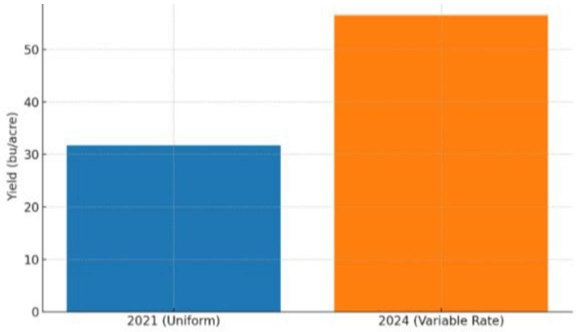

Fig. 1. Bar Chart Comparing Yield Under Uniform (2021) and Variable Rate (2024) Fertilizer Application

TABLE I. Table Comparing Yield Under Uniform (2021) and Variable Rate (2024) Fertilizer Application

Year	Average Yield (bu/ac)
2021 (Uniform)	31.68
2024 (Variable Rate)	56.51

The observed increase surpassed the genetic yield potential of the DEKALB hybrid, indicating that precision nutrient management was more influential than varietal differences. The uniform and variable rate yield maps are illustrated below. (see Figures 2 and 3).

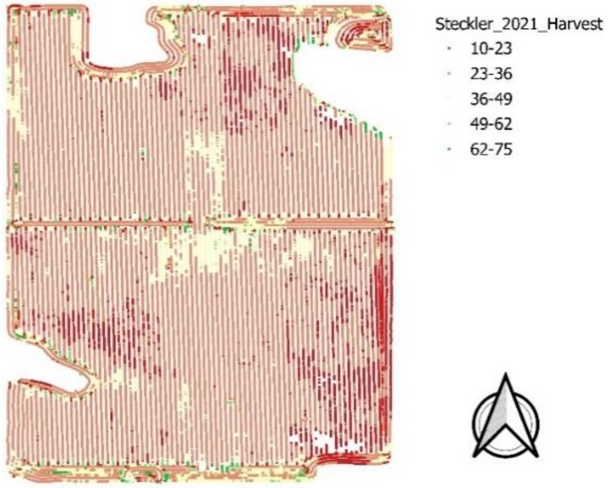

Fig. 2. Spatial Distribution of Yield in 2021 (Uniform Application).

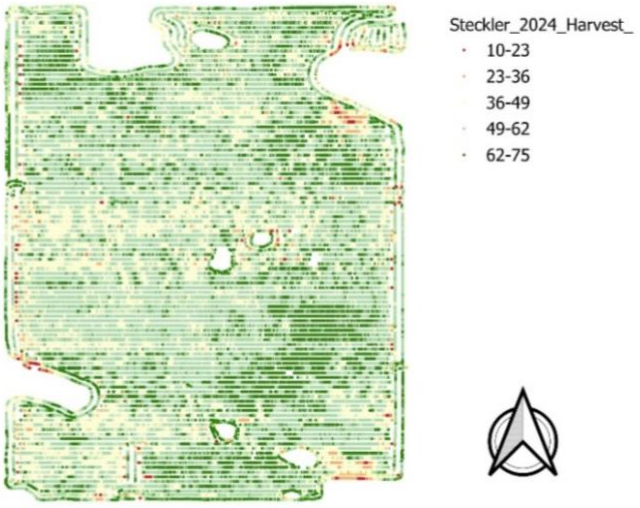

Fig. 3. Spatial Distribution of Yield in 2024 (Variable Rate Application).

Fertilizer application rates varied significantly across nutrients. Nitrogen decreased marginally from 116.1 lb/ac to 114.5 lb/ac, phosphorus declined from 50.5 lb/ac to 48 lb/ac, potassium increased from 10.1 lb/ac to 21 lb/ac, and sulfur decreased from 20.2 lb/ac to 18.2 lb/ac, see Table II. All changes were statistically significant based on Welch's two-sample T-tests ($p < 0.001$).

TABLE II. SUMMARY OF NUTRIENT APPLICATION RATES (2021 VS. 2024), INCLUDING P-VALUES

Variable	Mean_2021	Mean_2024	P_Value
N	116.0670837	114.5365766	8.71E-08
P	50.45547227	47.95479478	5.56E-90
K	10.05211063	21.00499759	0
S	20.18219021	18.23069683	0.00E+00
Yield	31.67607321	56.50967774	0

These nutrient shifts reflect spatially informed corrections made possible by VRT (see Figures 4 and 5).

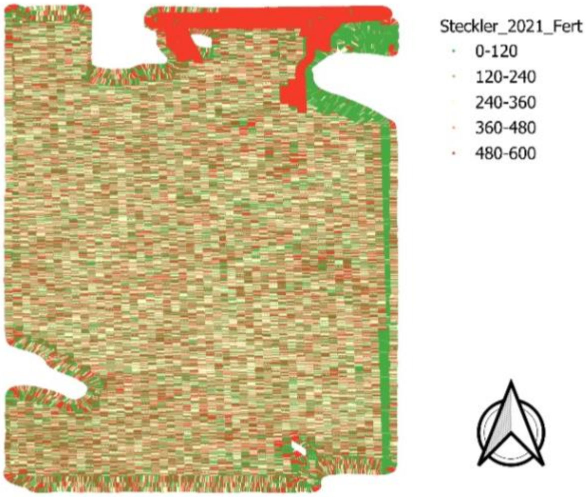

Fig. 4. Spatial Distribution of Fertilizer Application Rates: Uniform (2021)

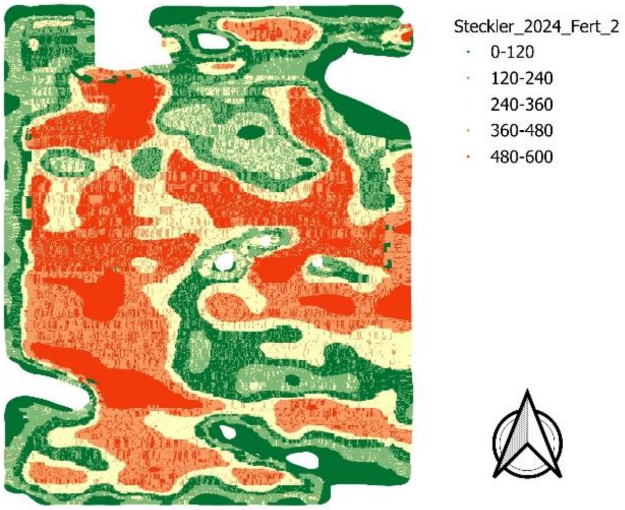

Fig. 5. Spatial Distribution of Fertilizer Application Rates: Variable Rate (2024)

Weather conditions in both seasons influenced crop growth and fertilizer efficiency. Based on Farmer's Edge station data (see Figures 6 and 7), cumulative precipitation in 2024 was higher and slightly better distributed during key phenological stages compared to 2021. The 2024 season also featured more moderate daytime temperatures and fewer high-heat stress days in June and July, which likely improved nutrient uptake efficiency and supported the higher yield. While the fertilizer application strategy was the primary variable under examination, this favorable weather context should be considered when interpreting performance outcomes [41].

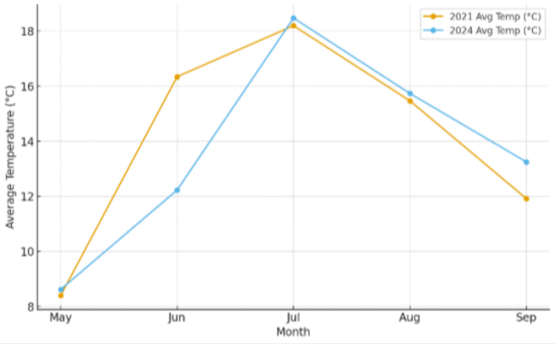

Fig. 6. Monthly Average Temperature (2021 vs 2024)

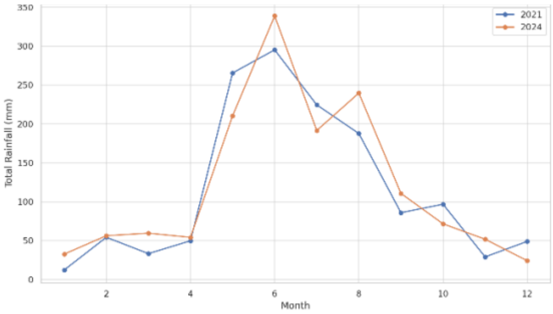

Fig. 7. Monthly total rainfall comparison between 2021 and 2024

The shift to variable rate application resulted in a reduction in total embodied GHG emissions. Using standard emission factors and conversion methods, the total emissions from fertilizer inputs decreased from 596.4 kg CO_2-eq/ha in 2021 (see Table III) to 586.7 kg CO_2-eq/ha in 2024, representing a net reduction of 9.7 kg CO_2-eq/ha (see Table IV). Nutrient-specific emissions, such as the 6.3 kg CO_2-eq/ha reduction for nitrogen, are outlined in Table IV.

TABLE III. FERTILIZER APPLICATION RATES AND EMBODIED CARBON EMISSIONS (2021)

Input	2021 Rate[a]	2021 Rate[b]	EF[c]	2021 Emissions[d]
N	116.1	130.1	3.51	456.7
P	50.5	56.6	1.011	57.2
K	10.1	11.3	0.576	6.5
S	20.2	22.7	3.35	76
Total	,	,	,	596.4

a. lb/ac

b. kg/ha

c. kg CO_2-eq/kg

d. kg CO_2-eq/ha

TABLE IV. FERTILIZER APPLICATION RATES AND EMBODIED CARBON EMISSIONS (2024) AND NET CHANGE (2021 VS 2024)

Input	2024 Rate[a]	2024 Rate[b]	EF[c]	2024 Emissions[d]	Net Change[d]
N	114.5	128.3	3.51	450.4	-6.3
P	48	53.8	1.011	54.4	-2.8
K	21	23.5	0.576	13.6	7.1
S	18.2	20.4	3.35	68.3	-7.7
Total	,	,	,	586.7	-9.7

a. lb/ac

b. kg/ha

c. kg CO_2-eq/kg

d. kg CO_2-eq/ha

Embodied energy analysis revealed a parallel decline. Energy use per acre dropped by approximately 62.6 MJ, driven mainly by reductions in nitrogen and sulfur. Although potassium use increased, the rise in energy input was offset by reductions in the other nutrients. Full calculations and coefficients are summarized in Tables V and VI.

TABLE V. FERTILIZER EMBODIED ENERGY USE (2021)

Nutrient	2021 Rate (lb/ac)	Energy Coefficient (MJ/lb)	2021 Energy (MJ/ac)
Nitrogen (N)	116.1	27.5	3,192.80
Phosphorus (P_2O_5)	50.5	5.04	254.5
Potassium (K_2O)	10.1	3.04	30.7
Sulfur (S)	20.2	19.05	384.8
Total	–	–	3,862.80

TABLE VI. FERTILIZER EMBODIED ENERGY USE (2024) AND NET CHANGE (2021 VS 2024)

Nutrient	2024 Rate (lb/ac)	Energy Coefficient (MJ/lb)	2024 Energy (MJ/ac)	Net Change (MJ/ac)
Nitrogen (N)	114.5	27.5	3,148.80	−44.0
Phosphorus (P_2O_5)	48	5.04	241.9	−12.6
Potassium (K_2O)	21	3.04	63.8	+33.1
Sulfur (S)	18.2	19.05	346.7	−38.1
Total	–	–	3,800.20	−62.6

Despite localized increases in potassium application, the overall environmental burden decreased while productivity sharply improved. This outcome highlights the dual benefits of VRFA, which enhances both economic performance and sustainability in canola production.

V. DISCUSSION

This research presents empirical evidence that VRFA considerably improves agronomic and environmental outcomes in commercial field settings. In this study, VRFA achieved a reduction in embodied fertilizer-related GHG emissions of 9.7 kg CO_2-eq/ha, while concurrently enhancing grain yield by 78.4 percent compared to uniform fertilization. The results surpass the usual VRFA yield gains of 5 to 20 percent documented in previous precision agriculture studies [3, 8], indicating that under optimal agronomic and climatic conditions, VRFA can provide transformative improvements rather than merely incremental ones.

The simultaneous improvements in productivity and sustainability are significant, as fertilizer inputs are among the primary contributors to agricultural energy demand and GHG emissions, especially nitrogen-based fertilizers characterized by high embodied carbon intensity [3]. VRFA optimized nutrient supply in accordance with the spatial variability of crop demand, thereby decreasing excessive applications of nitrogen and sulphur, which are linked to elevated carbon footprints, while focusing potassium inputs on areas that have been historically under-fertilized. This nutrient redistribution indicates that VRFA not only decreases input usage but also optimizes nutrient balance to enhance crop physiology and promote environmental stewardship. The observed increase in yield, alongside reduced emissions, indicates effective input reallocation rather than solely a decrease in input intensity.

Weather-related factors provide additional context for these outcomes. Empirical studies indicate that the timing of precipitation, temperature variations, and intra-seasonal weather fluctuations influence yield responses to variable rate technologies [47, 48]. Field observations in this study suggest that efficiency gains driven by VRFA were enhanced by more evenly distributed and agronomically suitable precipitation events in 2024, especially during key vegetative and reproductive phases in May, June, and August. In 2021, rainfall during critical growth periods was lower, even though overall seasonal totals were similar, with precipitation disproportionately concentrated in July (see Figure 8). The conditions in 2021 likely limited nutrient uptake and biomass accumulation, thereby diminishing the effectiveness of uniform fertilization and enhancing the relative benefits of VRFA in 2024.

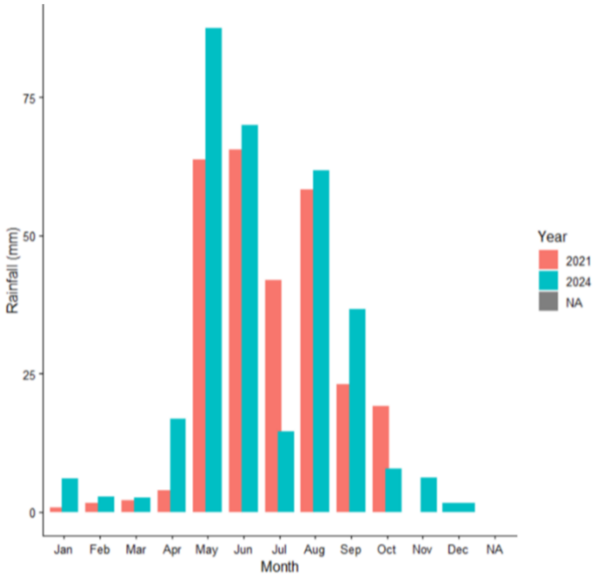

Fig. 8. Monthly total rainfall totals between 2021 and 2024

Collectively, these findings indicate that, in conjunction with favourable weather patterns, VRFA can substantially enhance both productivity and environmental performance beyond typical reported ranges. The integration of precision nutrient management with climate-resilient agronomic planning is essential, as interactions between weather and nutrients will increasingly influence fertilizer efficiency outcomes in changing climatic conditions.

In addition to in-season rainfall, moisture from the preceding year may have influenced yield variations between 2021 and 2024. Although total rainfall in 2020 exceeded that of 2023, a notable distinction emerges in late-season precipitation. August 2023 received substantially higher rainfall than August 2020, while subsequent months recorded almost similar totals. The late-season rainfall in 2023 likely increased soil moisture reserves and enhanced water availability for the beginning of the 2024 growing season (see Figure 9). While such carryover effects cannot be quantified precisely in this study, the improved soil moisture conditions in early 2024 may have complemented the benefits of VRFA, contributing to the substantial yield increase observed.

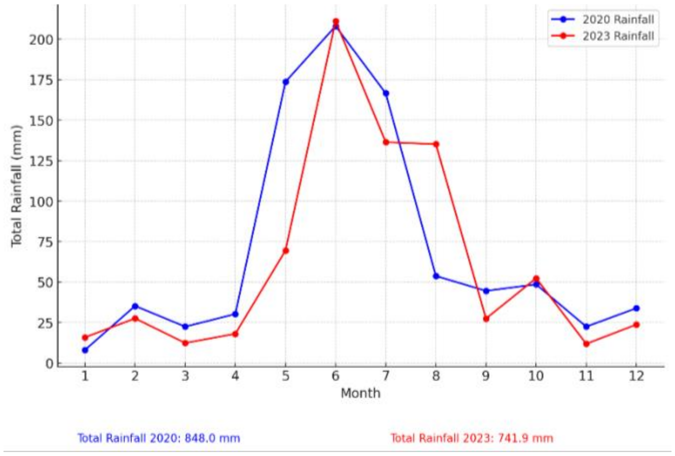

Fig. 9. Monthly total rainfall comparison between 2020 and 2023

Collectively, these findings indicate that the performance of VRFA in 2024 cannot be exclusively ascribed to precision input management. This reflects the interaction of VRFA with favourable weather conditions during the growing season and from previous year's rainfall patterns, highlighting the importance of interpreting agronomic and environmental outcomes within a broader climatic context.

The results of the 2024 season can also be interpreted through a wider lens. VRT is seldom a technology that transforms a field in a single attempt. Instead, its benefits tend to accumulate over time as the system learns, corrects, and gradually stabilizes [9, 49]. The two preceding corn seasons, both managed with VRT, played a role in shaping the landscape that 2024 inherited. Much of the spatial irregularity present in 2021 had already begun to soften during those intervening years [9]. When seen this way, the strong fertilizer-use efficiency and yield improvements observed in 2024 are not only the outcome of decisions made in that year but also represent a continuation of a longer process in which the field progressively aligned itself with the logic of variable rate management.

The analysis of embodied emissions highlights the importance of VRFA in strategies for sustainable intensification. Reductions in nitrogen and sulphur emissions underscore VRFA's contribution to decreasing the upstream carbon footprint of crop production, with energy use decreasing by approximately 62.6 MJ/ac relative to uniform application. Localized increases in potassium application resulted in some emissions; however, the overall net balance was distinctly positive. This substantiates the argument for VRFA as a fundamental practice in low-carbon agriculture, necessitating the simultaneous achievement of productivity and emissions targets.

These findings enhance the broader discourse on precision agriculture, which has frequently been fragmented by focusing on individual input types. Although numerous studies examine agronomic or environmental outcomes individually, there is a scarcity of research that quantifies both concurrently. This study provides explicit evidence that emissions savings and yield gains can coexist under VRFA, thereby enhancing the foundation for integrated sustainability assessments in crop production.

VI. LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

While making empirical contributions, this study has limitations that warrant acknowledgment. The analysis focused on one commercial farm in Alberta, and the results may not be applicable to other agro-ecological contexts with varying soils, climates, or management histories. The analysis quantified solely the embodied emissions associated with fertilizer manufacture and delivery, excluding soil-based nitrous oxide emissions and long-term effects on soil fertility. The dimensions are essential for a comprehensive sustainability assessment.

Subsequent research should extend these findings by broadening the geographic range of VRFA trials, utilizing multi-year datasets, and incorporating soil-based emissions monitoring. Research should examine the dynamics of producer adoption, focusing on cost-benefit trade-offs, barriers to implementation, and decision-making processes amid climate uncertainty. Integrating agronomic, economic, and environmental dimensions should enhance the understanding of VRFA's long-term role in sustainable agricultural systems.

VII. CONCLUSION

This research argues that VRFA improves agronomic performance and environmental sustainability in commercial canola production. Comparative field trials conducted at Steckler Farm in Alberta revealed a 78.4 percent increase in yield, alongside a reduction of 9.7 kg CO_2-eq/ha in fertilizer-related emissions and a decrease of 62.6 MJ/ac in embodied energy use. The findings indicate that precision nutrient management enhances the efficiency of crop input utilization by synchronizing fertilizer application with spatial variability within the field, resulting in increased productivity and reduced environmental impacts.

The yield gains observed in the VRFA system cannot be exclusively ascribed to cultivar differences. The 2024 hybrid (DEKALB 902TF) demonstrated a lower published yield potential compared to the 2021 hybrid (InVigor LR344PC); however, actual farm performance in 2024 surpassed anticipated benchmarks. Enhanced nutrient placement and improved fertilizer-use efficiency were the main factors contributing to productivity gains under VRFA.

Weather conditions served a moderating function. In 2021, precipitation predominantly occurred late in the season, thereby restricting early growth effectiveness during essential crop phases. The 2024 season experienced more uniform rainfall distribution during critical phenological stages, including establishment, vegetative development, and pod fill, supported by residual soil moisture from a favourable 2023 season. The findings underscore that the timing and distribution of precipitation, along with moisture carryover from the previous year, are critical factors influencing fertilizer efficiency and yield potential in Prairie cropping systems.

The novelty of this research is providing field-level evidence by simultaneously quantifying emissions, energy use, and yield, addressing a literature frequently characterized by theoretical, model-based, or single-metric assessments. The findings establish VRFA as a scalable, practical, and impactful precision agriculture method that can aid in achieving Canada's sustainable intensification objectives.

Further evaluation across diverse agro-ecological zones, crop types, and climatic conditions might be essential to enhance generalizability. Future research should integrate long-term climate variability and soil-water dynamics to enhance VRFA decision frameworks and quantify system-level benefits.

VRFA represents a practical and environmentally sustainable strategy that can enhance productivity in agriculture and other global production areas while decreasing carbon intensity. Considering global warming and the increasing importance of nutrient efficiency, VRFA presents a viable approach to sustainable crop production and resilient food systems.

VIII. LIST OF ABBREVIATIONS

Bushels Per Acre	bu/ac
Di-phosphorus Pentoxide	P_2O_5
Global Position System	GPS
Greenhouse Gas Emissions	GHG
Growing Degree Days	GDD
Kilograms Of Carbon Dioxide Equivalent Per Hectare	kg CO_2-eq/ha
Kilograms Per Hectare	kg/ha
Megajoules Per Hectare	MJ/ha
Nitrogen	N
Phosphorus	P
Potassium	K
Potassium Oxide	K_2O
Pounds	lbs
Sulfur	S
Variable Rate Fertilizer Application	VRFA
Variable Rate Irrigation	VRI
Variable Rate Pesticide Application	VRPA
Variable Rate Seeding	VRS
Variable Rate Technology	VRT

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1) *Conflict of Interest*

The authors of this publication declare there is no conflict of interest.

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4) *Declaration of Generative AI and AI-Assisted Technologies*

The authors used ChatGPT to assist with some language clarity and overall organization of the text. All content was reviewed, edited, and verified by the authors, who take full responsibility for the accuracy and integrity of the final article.

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