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Article

The Effect of Climate Smart Agricultural (CSA) Practices in Sustainability: A Case Study Focusing on Wheat Cultivation in Lithuania

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Abstract

Conventional agricultural production systems are increasingly challenged to balance environmental sustainability with economic performance, highlighting the need to systematically evaluate climate-smart agricultural practices as viable alternatives. The primary objective of the present work is to assess the environmental and economic benefits of implementing different Climate Smart Agricultural (CSA) practices in the agricultural sector. For this purpose, four different CSA practices, including intercropping, renewable energy, variable rate fertilizer and no-tillage system, were studied in wheat cultivation in Lithuania. Subsequently, their environmental and economic performance was compared to a conventional wheat producing farm. For the environmental performance, Life Cycle Assessment (LCA) analysis was performed following the respective ISO recommendations. Based on the results, the incorporation of CSA practices in the agricultural sector can lead not only to substantial improvements in environmental performance but also to notable economic benefits, depending on the selected practice. Regarding their environmental performance, the most prominent studied CSA was renewable energy that minimizes greenhouse gas emissions, followed by variable rate fertilization. The economic analysis showed intercropping to be the most profitable option, with the total profit being 792 €/ha, while no-tillage also showed competitive results, with subsidies in each studied system playing a major role in the economic performance. Conversely, variable rate fertilization and renewable energy integration highlighted trade-offs between environmental advantages and short-term economic feasibility. Overall, the adoption of CSA practices represents a promising pathway toward more sustainable and resilient agri-food systems.

Keywords: climate smart agriculture; wheat cultivation; sustainability; life cycle assessment; life cycle costing

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1. Introduction

The increasing need to address climate change, the demand for climate-neutral production systems and the limited availability of natural resources has made it imperative to adopt more sustainable and resilient practices in all industrial sectors, including agriculture [1,2]. In this context, the adoption of Climate Smart Agriculture (CSA) practices emerges as an appealing solution that simultaneously aims to improve productivity, enhance adaptability to climate change and reduce the environmental impacts of agricultural

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activity [3]. Wheat is one of the most important cereals and a core component of the diet for a large part of the world's population [4]. However, conventional wheat cultivation methods are often associated with adverse environmental impacts, such as elevated greenhouse gas emissions and consumption of significant quantities of chemical agents (i.e., fertilizers), which makes it necessary to search for and evaluate alternative and more-sustainable solutions [5,6]. Among the most promising CSA practices are intercropping of wheat with other crops, installation of equipment for the generation of renewable energy, variable-rate fertilizer application, and no-tillage farming [7].

Recent insights from the Food and Agriculture Organization (FAO) further emphasize that CSA must be approached as a holistic framework that enhances productivity, strengthens resilience, and reduces greenhouse gas emissions while ensuring long-term sustainability of food systems [8]. According to the FAO, CSA practices should be evaluated not only at the field level but also within broader food system interactions, considering resource limitations, climate vulnerabilities, and socio-economic constraints that influence adoption and effectiveness [8].

Intercropping, particularly the combination of pea and wheat, is a sustainable agricultural practice that involves growing two different crops simultaneously on the same field [9,10]. In a pea-wheat intercrop system, wheat plays a protective role for the more delicate pea plants, shielding them from harsh weather conditions and suppressing weed growth through canopy coverage [7,11,12]. This symbiotic relationship allows for better resource utilization, as the two crops exploit different soil layers and nutrients, enhancing overall field productivity and soil health [7,11,13]. No-tillage systems in wheat farming offer a more natural and less disruptive way to grow crops by leaving the soil undisturbed throughout the growing cycle [14]. Instead of plowing or turning the soil, farmers plant wheat directly into the previous season's crop residues, thus the structure of soil remains intact, which helps retain moisture, reduce erosion, and support beneficial organisms like earthworms and microbes [15]. Variable Rate Fertilizer (VRF) application is a precision agriculture practice that enables the strategic and efficient use of fertilizers by tailoring input rates to the specific needs of different zones within a cultivated field [16]. This approach is grounded in the analysis of spatial data collected through technologies such as soil sampling, yield mapping, GPS, and remote sensing, which are synthesized into a pre-set field map [17,18]. Integrating systems that can exploit solar energy into farming land use offers a sustainable way to produce renewable energy while still using the land for agriculture, such as grazing or forage production [19]. The exploitation of solar energy involves installing solar panels above the cultivation, allowing dual use of the area for both energy and food production [19]. This approach helps optimize land use, supports the energy transition, and can contribute to the farm's economic resilience [20].

The aforementioned practices exhibit great potential to significantly improve to the overall environmental and economic sustainability of the agricultural sector [7,13]. However, a comprehensive assessment of the environmental and economic performance of CSA practices is necessary to highlight their benefits. Life Cycle Assessment (LCA) is a well-established methodology for assessing the environmental impacts of product systems throughout their life cycle, from the extraction of raw materials to the end-of-life of the final products [21]. LCA can identify hotspots in resource use, emissions and waste generation, and provide practical guidance for improving environmental performance [22]. On the other hand, Life Cycle Costing (LCC) is a methodology that takes into consideration all costs associated with the product system, including investment, operation, and end-of-life expenses, thus identifying financial burdens, and can be a helpful solution in optimizing the economic efficiency of the system [23].

The main goal of the present work is to evaluate the environmental performance of incorporating different CSA practices in wheat cultivation and compare their performance with a conventional wheat cultivation system (Baseline—BL). For this purpose, the environmental impact of a conventional wheat cultivation system was assessed, since wheat is a vital element of human diet and nutrition, and subsequently five different scenarios were evaluated, with each one assessing the performance of a studied CSA practice. Although several studies have examined the potential of CSA, a limited number of studies have proceeded to a quantitative assessment of the environmental outcomes in real farming conditions. The present work, through the application of LCA and LCC to a wheat cultivation case study, seeks to provide evidence-based knowledge on how CSA practices can improve the sustainability of the agricultural sector. This research contributes to the achievement of several United Nations Sustainable Development Goals, particularly SDG 2 (Zero Hunger) by promoting sustainable agricultural practices, SDG 12 (Responsible Consumption and Production) through improved resource efficiency, SDG 13 (Climate Action) by reducing environmental impacts of crop production, and SDG 7 (Affordable and Clean Energy) through the integration of renewable energy in agricultural systems.

2. Materials and Methods

LCA analysis was conducted based on the recommendations established by the ISO 14040 recommendations series (14040:2006 and 14044:2006) [24]. The impact assessment methodology for the present work was ReCiPe 2016, hierarchist, with its main objective being the transformation of Life Cycle Inventory results into a limited number of environmental impact scores using characterization factors. LCA analysis was performed using the LCA for Experts software (version 10.6.2.9, Sphera Solutions GmbH, Stuttgart, Germany).

LCC analysis was performed using Microsoft Excel (v15.0) to assess all relevant economic flows. This study focused on operating expenditures (OPEXs), while capital expenditures (CAPEXs) were determined for the CSA of renewable energy and variable rate fertilization, since they encompassed the purchase and installation of solar panels and of new equipment, respectively.

2.1. Functional Unit

The selected functional unit for the LCA and LCC analyses is 1 ha of cultivated area.

2.2. System Boundaries

The objective of the study is to compare the application of the CSA practices with conventional farming in wheat cultivation over a period of 1 year. To achieve this, a cradle-to-gate approach was adopted, focusing solely on processes occurring within the farm. More specifically, the boundaries of the system encompass all stages involved in wheat cultivation. Upstream processes related to agricultural inputs (e.g., fertilizers and electricity) were considered, in line with standard LCA methodology, while downstream stages such as processing, packaging, distribution, and consumption were excluded.

2.3. Data Requirements

To conduct the LCA analysis, data were gathered through the distribution of questionnaires to relevant stakeholders, including farmers and advisors, supplemented by data from verified databases such as Ecoinvent, Agri-footprint and Agribalyse, which cover the geographical area of the European Union 28 (EU-28). The collected data refer to the years 2024–2025. The present research has been performed in the context of the BEATLES project (HORIZON EUROPE—Grant id: 101060645). Data are specified for the activities of 1 Use Case in Lithuania, where different CSA practices in wheat cultivation have been studied. Data were collected from project partners located in Lithuania, who were responsible for communicating with farmers that apply the studied CSA practices. All GDPR procedures were followed and the quality of the obtained data followed the directions of the Project's Management Handbook and the directives of the European Union.

2.4. Assumptions and Limitations

For the LCC of all cultivation systems, including the baseline, a subsidy of 150 €/ha is assumed [25]. Additionally, in the no-tillage CSA practice, an additional subsidy of additional 66 €/ha for eco-scheme is considered [26]. In all studied systems, other general costs amount to 5% of all cost flows.

For the LCC analysis of the variable rate fertilizer CSA practice, the total capital expenditure for the purchase of the equipment amounts to 47,000 €, with a depreciation period of 5 years. Specifically, the equipment consists of a navigational system, narrower wheels for tractor, and smart fertilizer spreader.

For the LCC analysis of the renewable energy CSA practice, the following factors were assumed. Firstly, the average installation cost of the solar panels is 703 €/kW, thus the CapEx for the installation of the 32 kW solar panel systems was calculated at 22,500€. This cost is supported by the EU Next Generation Funds subsidy scheme [27], and a straight-line depreciation method was assumed for the cost that was not covered by the subsidy scheme (10,500 €), with a depreciation period of 5 years. Additionally, the added income from selling the generated electricity to grid is estimated at 0.3 €/kWh.

Additionally, due to the fact that some of the studied CSA practices, like NT and VRF can often result in a yield drag in early years or aim to optimize the yield-to-input ratios, a sensitivity analysis for these two CSA practices has also been evaluated, with the yields varying by $\pm 5\%$ and $\pm 10\%$. However, due to the fact that the functional unit of the present study was set at 1 ha of cultivated land, results regarding the environmental performance will remain the same, while the results of the economic footprint will be influenced.

Direct and indirect soil N_2O emissions resulting from nitrogen fertilizer application were explicitly quantified following the IPCC Guidelines for National Greenhouse Gas Inventories using Tier 1 emission factors [28]. Emissions from direct soil processes as well as indirect pathways via volatilization and leaching were incorporated into the life cycle inventory, ensuring a comprehensive assessment of greenhouse gas emissions from wheat cultivation.

2.5. Life Cycle Inventory (LCI)

Table 1 provides the basic information regarding the cultivation period and area cultivated for each CSA.

Table 1. Cultivation period and area of each studied system.

Studied System	Cultivation Period	Location of Farm (Lithuania)	Cultivation Area (ha)
Baseline (BL)	September 2022–August 2023	Alytus	5
Intercropping (IC)		Alytus	220
No Tillage (NT)		Alytus	170
Variable Rate Fertilizer (VRF)		Vilkaviškis	170
Renewable Energy (RE)		Šakiai	112

The Life Cycle Inventory (LCI), compiled from data collected through interviews with relevant stakeholders and supplemented with relevant literature sources, is summarized in Table 2.

Table 2. LCA inventory of the baseline and the studied CSA practices.

Parameter	Baseline (BL)	Intercropping (IC)	No Tillage (NT)	Variable Rate Fertilizer (VRF)	Renewable Energy (RE)
			Inputs		
Cultivation area (ha)	1	1	1	1	1
Wheat seeds (kg)	200	100	200	200	200
Pea seeds (kg)	-	80	-	-	-
P fertilizer (kg)	6	6	6	-	6
N fertilizer (kg)	66	66	66	30.6	66
Herbicides (kg)	0.96	0.96	0.96	0.96	0.96
Water (m^3)	0.2	0.2	-	0.2	0.2
Diesel (L)	92	101	78.2	82.9	92
			Outputs		
Grains (tn)	5.025	5.19	5.025	5.025	5.025
Packaging waste (kg)	0.5	0.5	0.5	0.5	0.5
			Emissions to air		
Herbicides (g) [29]	0.033	0.033	0.033	0.033	0.033
N_2O from N fertilizer (kg)	1.036	1.036	1.036	0.480	1.036
			Emissions to water		
Herbicides (g) [29]	2.72×10^{-6}	2.72×10^{-6}	2.72×10^{-6}	2.72×10^{-6}	2.72×10^{-6}
N_2O from N fertilizer (kg)	0.1036	0.1036	0.1036	0.0480	0.1036
			Emissions to soil		
Herbicides (g) [29]	222	222	222	222	222
N_2O from N fertilizer (g)	233	233	233	108	233
			Avoided Products		
Electricity (kWh)	-	-	-	-	8000

3. Results

3.1. LCA Results

The LCA results of the baseline scenario and of the different CSA studied in the present work are depicted in Figure 1 and Table 3.

The comparative LCA analysis revealed that the implementation of the different CSA practices substantially improved the environmental performance of wheat cultivation compared to the baseline scenario of a conventional cultivation product system in Lithuania.

Global warming potential (GWP) in the baseline system was evaluated at 580.39 kg CO_2 eq. per ha of cultivated land. All CSA practices demonstrated significant reductions, with the exception of the no tillage (NT) CSA, which resulted in a moderate decrease of 1% compared to the baseline. The most significant reduction was observed in the renewable energy (RE) scenario, which achieved a decrease of 349%, largely attributed to the generation of electricity from the exploitation of solar panels. However, it is worth mentioning that if the energy production in the RE CSA scenario is excluded from the system boundaries, the results in all studied categories remain the same to the ones achieved in the baseline, since there is no change in the inputs and outputs of the studied systems.

Terrestrial acidification and freshwater eutrophication potentials also exhibited a significant improvement across all studied CSA. Variable rate fertilizer (VRF) achieved almost the complete elimination of eutrophication potential, with 99% reduction, whereas the utilization of RE decreased the terrestrial acidification potential by 60%. Similar trends were observed in fossil resource scarcity, where RE achieved a 335% reduction, while VRF reduced the impact by 28%, respectively.

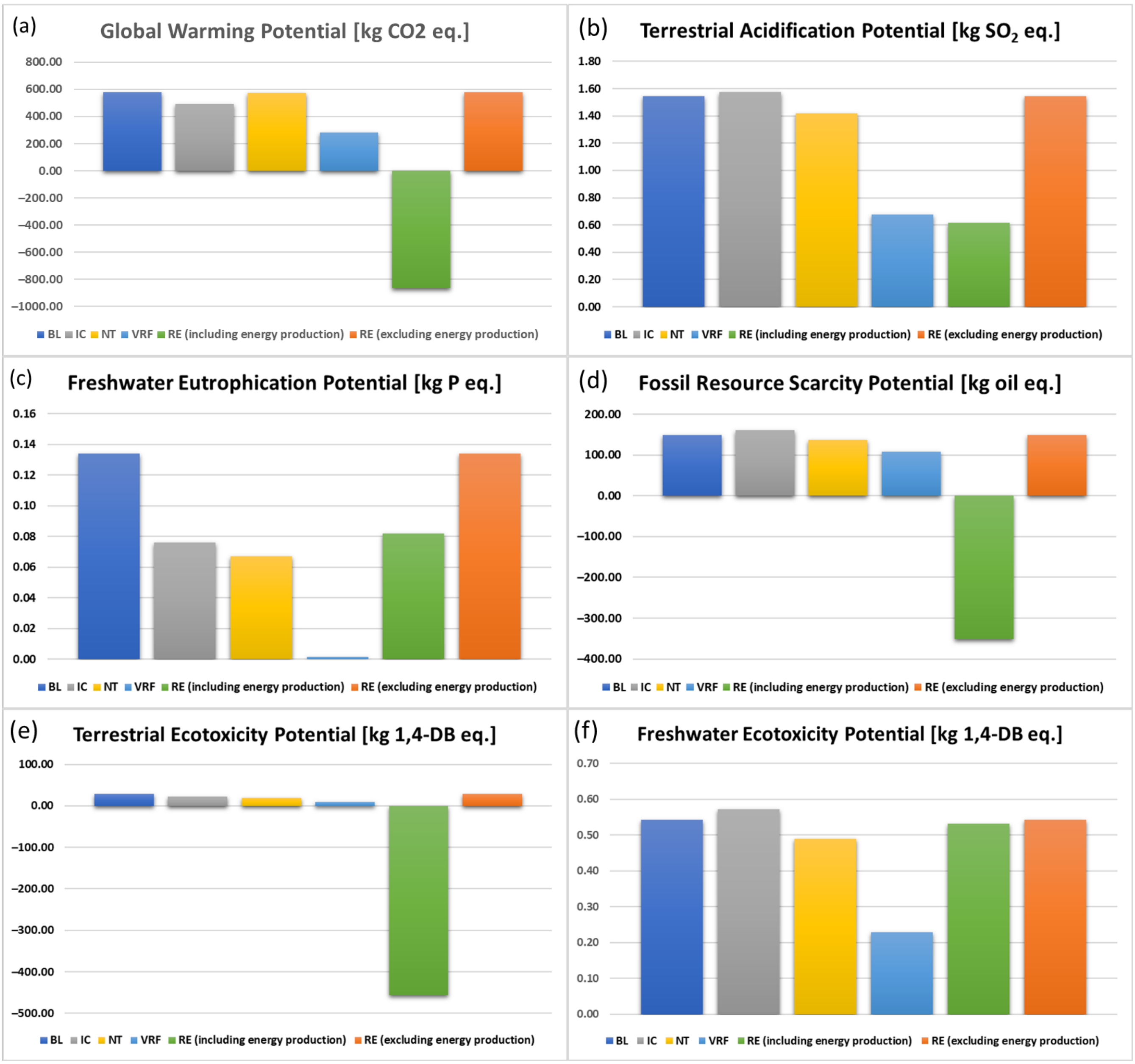

Figure 1. Environmental impact of the baseline (BL), intercropping (IC), no tillage (NT), variable rate fertilizer (VRF), and renewable energy (RE) with inclusion and exclusion of the energy production on (**a**) global warming potential (kg CO_2 eq.), (**b**) terrestrial acidification potential (kg SO_2 eq.), (**c**) freshwater eutrophication potential (kg P eq.), (**d**) fossil resource scarcity potential (kg oil eq.), (**e**) terrestrial ecotoxicity potential (kg 1,4-DB eq.), and (**f**) freshwater ecotoxicity potential (kg 1,4-DB eq.).

Ecotoxicity-related impacts followed comparable patterns. Terrestrial ecotoxicity was reduced by up to 1712% in the RE scenario, while VRF decreased impacts by 64%. Freshwater ecotoxicity reductions were more modest, with NT and VRF performing better than intercropping, which presented a slightly increased value compared to the baseline (+5%).

Overall, CSA practices demonstrated distinct but complementary environmental benefits, with renewable energy integration and variable rate fertilization providing the largest reductions across most categories. A more detailed discussion about the results regarding the environmental performance of the CSAs is described in Section 4.

Table 3. Comparison of the environmental impacts between the baseline scenario and the studied CSA practices.

Impact Category	Baseline (BL)	Intercropping (IC)	No Tillage (NT)	Variable Rate Fertilizer (VRF)	Renewable Energy (RE)	
					Including Energy Production	Excluding Energy Production
Global warming potential (kg CO_2 eq.)	580.39	−16%	−1%	−51%	−349%	-
Terrestrial acidification potential (kg SO_2 eq.)	1.54	+2%	−8%	−56%	−60%	-
Freshwater eutrophication potential (kg P eq.)	0.13	−43%	−50%	−99%	−39%	-
Fossil resource scarcity potential (kg oil eq.)	149.75	+7%	−9%	−28%	−335%	-
Terrestrial ecotoxicity potential (kg 1,4-DB eq.)	28.29	−19%	−30%	−64%	−1712%	-
Freshwater ecotoxicity potential (kg 1,4-DB eq.)	0.54	+5%	−10%	−58%	−2%	-

3.2. LCC Results

The LCC results of the baseline scenario and of the different CSA studied in the present work are depicted in Table 4 and Figure 2.

Table 4. Comparison of the LCC results between the baseline scenario and the studied CSA practices.

Cost Category (€/ha)		Baseline (BL)	Intercropping (IC)	No Tillage (NT)	Variable Rate Fertilizer (VRF)	Renewable Energy (RE)
Expenses	Diesel	141.31	107.52	105.98	141.31	141.31
	Water	0.02	0.02	-	0.02	0.02
	Wheat seeds	188	180	188	188	188
	Fertilizers	26.04	68	26.04	3.6	26.04
	Herbicides	5.44	-	5.44	5.44	5.44
	Other general costs	10.82	26.87	9.76	10.15	10.82
	Equipment use and maintenance	175	175	225	226.86	179.66
	Equipment depreciation (5 years)	-	-	-	55.96	51.79
	Total	546.64	567.41	560.23	631.34	603.28
Revenues	Wheat grains	1135	-	1135	1135	1135
	Wheat and pea grains	-	1199.22	-	-	-
	Subsidies	150	150	216	150	150
	Electricity	-	-	-	-	71.43
	Total	1285	1349.22	1351	1285	1356.53
Profit		738.36	791.81	790.77	653.66	753.25
Operational margin (profit excluding subsidies)		588.36	641.81	574.77	503.66	603.25

The LCC analysis revealed significant variability in the economic performance of the studied CSA practices compared to the baseline scenario, which exhibited a profit of 738 €/ha. Intercropping slightly improved profitability to 792 €/ha, as additional costs for pea seeds and higher diesel consumption were offset by revenues from combined grain sales. Similarly, the no-tillage system achieved a profit of 791 €/ha, largely due to savings from reduced water use and eligibility for eco-scheme subsidies, despite higher equipment-related costs. In contrast, variable rate fertilization underperformed economically, yielding a profit of 654 €/ha. Although this practice reduced fertilizer and diesel inputs, the high capital expenditure and depreciation costs of precision equipment outweighed the operational savings. Renewable energy integration also showed a modest improvement over the baseline, with revenues from electricity sales compensating for the depreciation of the solar panel system not covered by subsidies and the total revenue value being 753 €/ha.

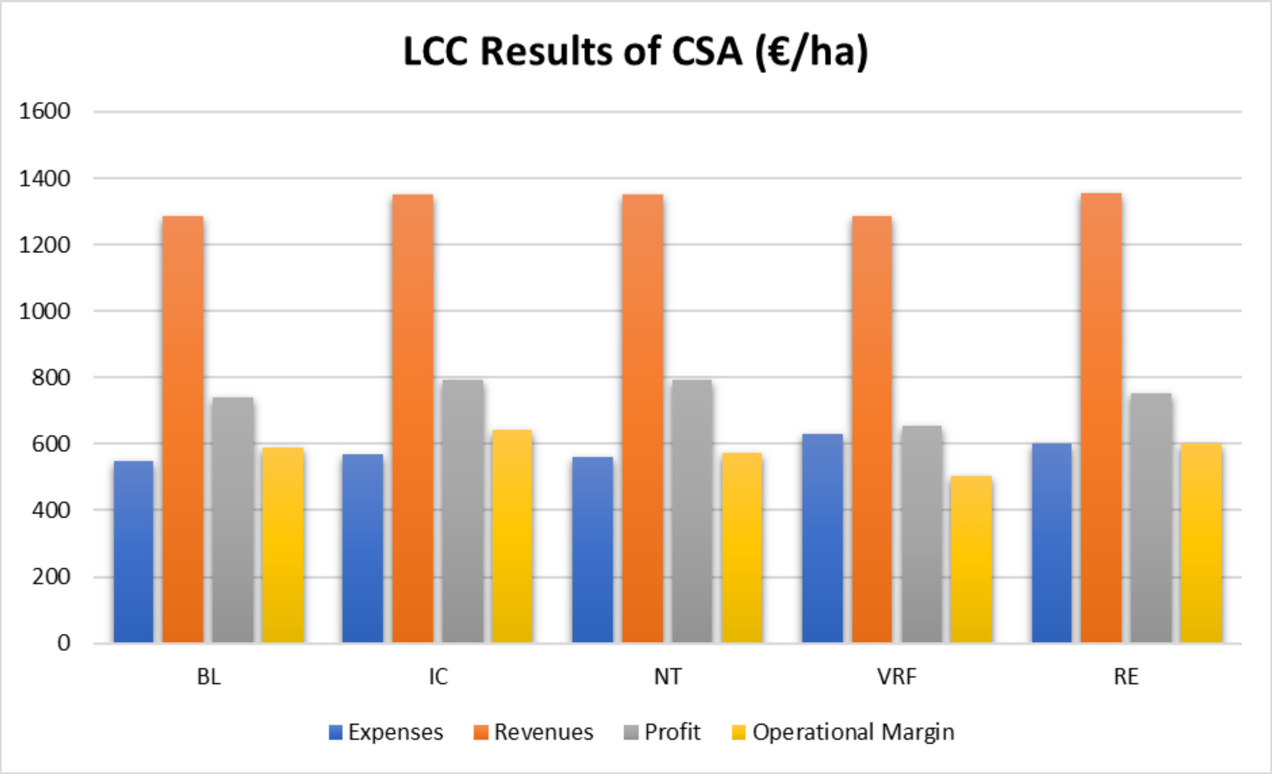

Figure 2. Economic performance of the baseline (BL), intercropping (IC), no tillage (NT), variable rate fertilizer (VRF), and renewable energy (RE).

Overall, the results highlight that while all CSA practices influence farm economics, their impact varies substantially. Practices such as intercropping and no tillage provide measurable economic advantages, whereas others, like variable rate fertilizer, may require long-term adoption and supportive policy frameworks to become economically competitive. Additionally, it is worth mentioning that subsidies can influence the overall economic performance of the farm, such as in the CSA of no tillage, thus careful evaluation of all economic factors should be taken into account. A more detailed discussion about the results regarding the economic performance of the CSAs is described in Section 4.

3.3. Sensitivity Analysis

The results of the sensitivity analysis in the economic performance of the NT and VRF CSA practices are presented in Figures 3 and 4, respectively.

To assess the robustness of the economic results against yield variability, a sensitivity analysis was conducted for the NT and VRF scenarios by varying wheat yield by ±5% and ±10% relative to the baseline yield, while keeping all cost inputs constant. The baseline scenario was retained as a reference point.

For the NT CSA practice, the baseline yield scenario resulted in a profit of 790.77 €/ha and an operational margin (excluding subsidies) of 574.77 €/ha, compared to 738.36 €/ha and 588.36 €/ha, respectively, for the baseline system. A 10% decrease in yield reduced profit to 677.27 €/ha, with the operational margin declining to 461.27 €/ha, indicating that the economic advantage of no-tillage is sensitive to yield penalties. Conversely, a 10% increase in yield substantially improved performance, increasing profit to 904.27 €/ha and the operational margin to 688.27 €/ha. These results suggest that while no-tillage can remain economically competitive under moderate yield reductions, its profitability is strongly enhanced when yield levels are maintained or improved.

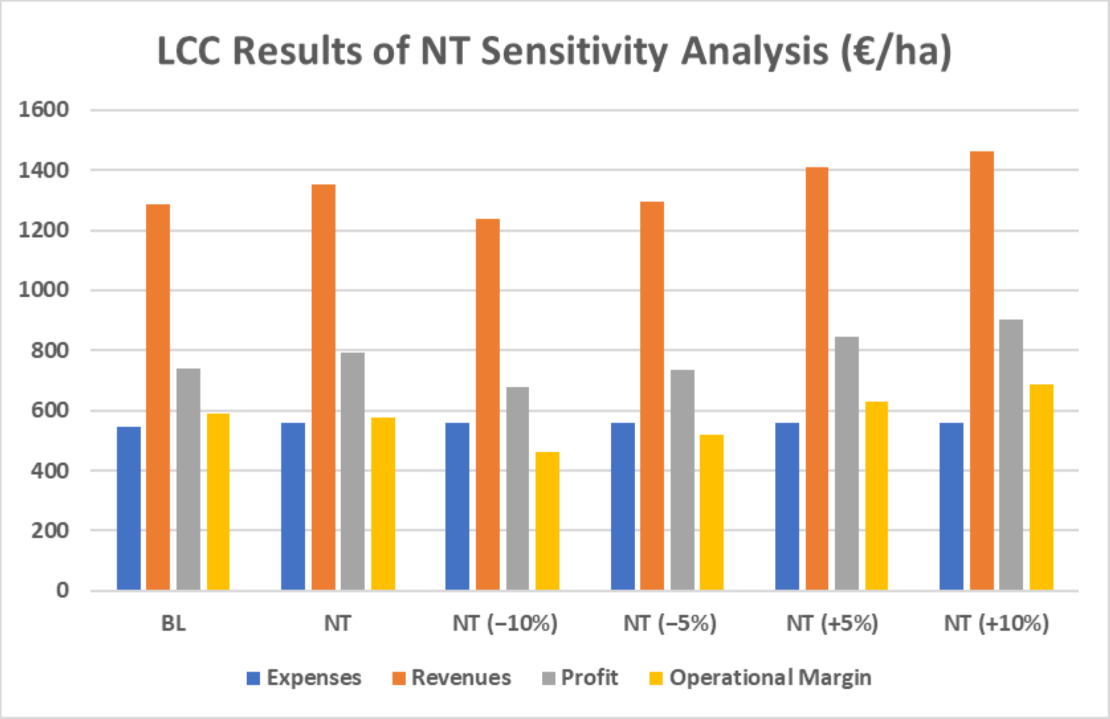

Figure 3. Sensitivity analysis in the economic performance of NT CSA scenario.

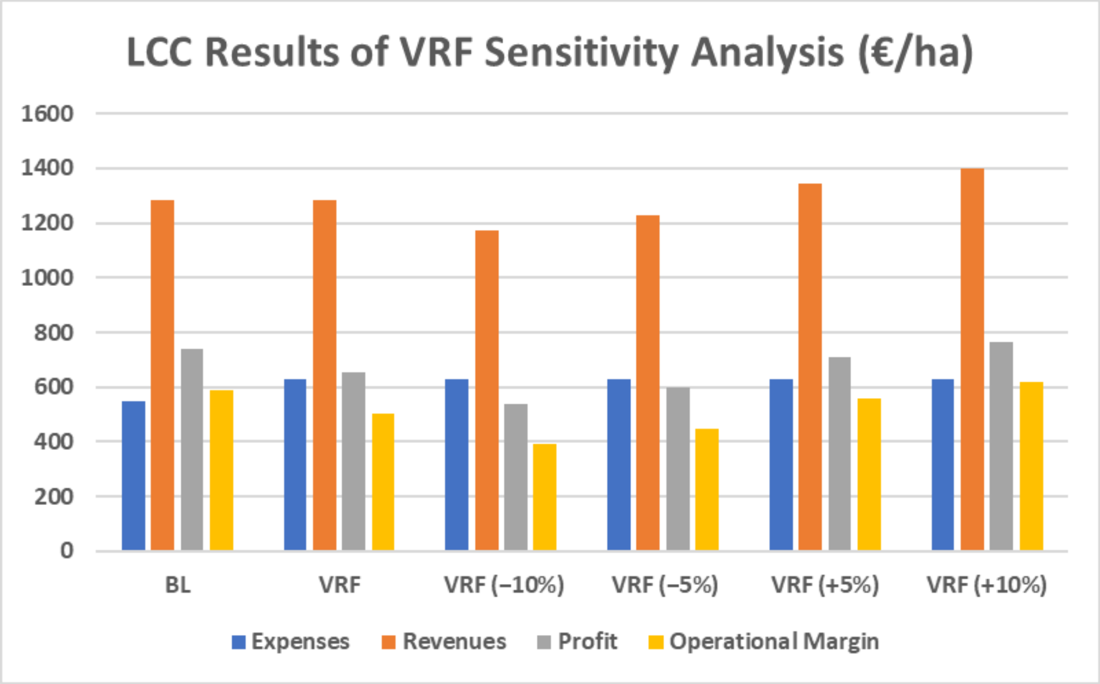

Figure 4. Sensitivity analysis in the economic performance of VRF CSA scenario.

For the VRF scenario, the baseline yield resulted in a profit of 653.66 €/ha and an operational margin of 503.66 €/ha, both lower than those of the baseline system. Under a 10% yield reduction, profitability declined markedly to 540.16 €/ha, with the operational margin decreasing to 390.16 €/ha, highlighting the vulnerability of VRF to yield losses given its higher capital and equipment-related costs. In contrast, yield increases significantly improved economic outcomes: at +10% yield, profit rose to 767.16 €/ha, and the operational margin reached 617.16 €/ha, surpassing the baseline system.

Overall, the sensitivity analysis demonstrates that yield assumptions play a critical role in determining the economic sustainability of agronomic CSA practices. No-tillage shows moderate resilience to yield variability, while variable rate fertilization exhibits stronger dependence on yield gains to offset higher fixed costs. These findings confirm that assuming identical yields across scenarios may mask important trade-offs and that incorporating yield variability is essential for a realistic economic assessment of Climate-Smart Agricultural practices.

4. Discussion

4.1. LCA Discussion

The findings of this study confirm the substantial potential of CSA practices to enhance the environmental sustainability of wheat cultivation, aligning with previous literature on the environmental benefits of precision agriculture and renewable energy integration [30,31]. The observed reductions in the greenhouse gas emissions in the scenarios of renewable energy highlight the importance renewable energy production and optimization or minimization of additional chemical inputs in agriculture in lowering emissions. Similar studies on solar-powered farms reported comparable outcomes, indicating that the aforementioned CSA practices offer significant leverage points for climate-smart farming [32–34]. However, it is worth mentioning that the incorporation of renewable energy does not influence the agricultural efficiency; thus, the inputs and outputs of the farm in terms of agricultural needs and products remain the same. Therefore, the inclusion of such a CSA constitutes the farm as more sustainable and not necessarily the wheat itself, since the exclusion of the generated electricity from the system would translate to wheat having the same environmental performance as in the baseline system [35].

Intercropping also demonstrated clear benefits in terms of environmental performance in certain impact categories; however, the slight increase in freshwater ecotoxicity suggests the need for careful management of crop interactions and agrochemical inputs [36,37]. This slight increase in freshwater ecotoxicity and terrestrial acidification potential can be attributed to the elevated diesel consumption and the inclusion of the pea seeds in the farm [38,39].

Variable rate fertilization emerged as particularly effective in minimizing the required fertilizers dosage, thus almost completely eliminating freshwater eutrophication potential. Specifically, in the VRF practice, the phosphorous fertilizer is not applied and the amount of nitrogen fertilizer is substantially lower compared to the baseline system. Additionally, the improvement in the environmental performance is also attributed to the decrease in diesel consumption [40,41]. This outcome supports findings from precision fertilization trials, which emphasize the efficiency gains of site-specific nutrient management [42]. No-tillage systems, while yielding more moderate improvements, still provided consistent reductions across multiple categories, conforming with earlier reports on their benefits in the agricultural sector [43]. The slight improvement in greenhouse gas emissions is attributed to the decrease in diesel consumption in this system. Additionally, it is worth mentioning that the baseline system did not rely heavily on wheat being irrigated, with small quantities of water being used, thus the minimization of water consumption in the no-tillage system did not have a significant influence in the overall environmental performance.

Notably, the renewable energy scenario achieved exceptionally high reductions across most impact categories, driven by the displacement of conventional electricity generation. While these values pinpoint the significant role of renewable integration, careful interpretation of this CSA should be performed. The scalability of such systems depends on farm-level investment capacity, regional solar potential, and supportive policy frameworks.

The obtained results indicate that all the examined CSA practices are effective to a certain extent, each with its own improvements and benefits in different environmental impact categories. Additionally, their combination may prove to be even more efficient and beneficial, as it can leverage their complementary actions. However, the continued application and exploitation of the LCA methodology remains crucial to validate and verify the real effectiveness and benefits of these practices in field conditions. Furthermore, the present study focuses on the implementation of CSA practices in Lithuania, and the results of these CSA in different countries may exhibit different outcomes.

4.2. LCC Discussion

The LCC analysis demonstrated that the economic feasibility of CSA practices is highly dependent on their cost structures, subsidy mechanisms, and revenue streams. Intercropping and no-tillage are competitive, albeit with only marginal improvements over the baseline. These results suggest that such practices may offer a low-risk pathway for farmers seeking incremental economic and environmental benefits. Additionally, it is worth mentioning that in the no-tillage CSA practice, subsidies play a crucial role in the improvement of the economic performance of the system. If the additional 66 €/ha are excluded, the total profit of the system is slightly less compared to the baseline system, since the savings in other cost categories, such as diesel and water, do not efficiently compensate the elevated costs regarding the use and maintenance of equipment. On the other hand, variable rate fertilization reduced operational costs but was hindered by high capital investment, which limited its profitability in the short term. Renewable energy integration, while delivering only modest immediate gains, provides long-term stability and resilience against energy price fluctuations, particularly under supportive policy schemes.

Importantly, the LCC findings emphasize that the most environmentally favorable practices are not always the most profitable in the short term. For instance, VRF offered strong reductions in environmental impacts but was economically challenging, while renewable energy showed a similar trade-off. These insights underline the importance of policy incentives, subsidy schemes, and technological cost reductions in enhancing the adoption of such practices.

4.3. Replicability of Results

The repeatability of the obtained results depends on site-specific agronomic, climatic, and socio-economic conditions, which may influence both the environmental and economic performance of the evaluated Climate Smart Agricultural practices. While the methodological framework applied in this study, particularly the Life Cycle Assessment and economic evaluation, can be consistently replicated in other contexts, the magnitude of the impacts may vary across different geographical areas due to differences in soil characteristics, climate patterns, input availability, energy mixes, and policy-driven subsidy schemes. Therefore, future research should apply the proposed assessment framework across diverse agro-ecological zones and farming systems to validate the robustness of the findings and to better understand the transferability of climate-smart practices under varying environmental and management conditions.

5. Conclusions

The results of this study demonstrate that the implementation of Climate Smart Agriculture practices can considerably enhance the environmental and economic performance of wheat cultivation in Lithuania. Across the scenarios examined, each CSA practice delivered distinct sustainability advantages, highlighting the value of diversified strategies rather than a single uniform solution. Renewable energy integration and variable rate fertilization led to the most pronounced reductions in environmental impacts, confirming their potential to strengthen climate mitigation efforts when appropriate infrastructure and policy support are available. Intercropping and no-tillage systems provided consistent environmental improvements while also offering competitive economic outcomes, emphasizing their suitability for farms seeking low-risk and operationally feasible transitions toward sustainability.

The economic analysis revealed that profitability varies significantly across CSA options, with intercropping and no-tillage performing favorably, while renewable energy and variable rate fertilization require longer time horizons or targeted subsidies to achieve economic parity with conventional practices. These results align with FAO recommendations, which underline that the effectiveness of CSA depends on local contexts, supportive governance, and the capacity of farmers to invest in new technologies.

Overall, the findings highlight that CSA practices can serve as practical pathways toward more resilient and sustainable wheat production systems, provided that their implementation is tailored to local conditions and supported by coherent policy measures. Future work should build on these insights by examining combinations of CSA practices over multiple growing seasons and across diverse pedoclimatic regions, enabling a more comprehensive understanding of long-term environmental and economic synergies.

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Informed Consent Statement: Informed consent was obtained from all participants in the project's activities.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Author Linas Didžiulevičius was employed by the company Beta via Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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