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ARTICLE

Rural Agricultural Efficiency, Climate Sustainability, and Economic Performance: An Examination of Organic and Conventional Farming

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ABSTRACT

Organic farming has emerged as a sustainable alternative to conventional farming, providing potential benefits in environmental conservation, crop quality, and market access. This study measures the impact of organic farming on agricultural productivity, resource utilisation, environmental sustainability, and trade competitiveness in Punjab,

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India. A comparative analysis of organic and conventional farming was conducted, focusing on key metrics such as crop yield per hectare, soil health, biological diversity, carbon footprint, and market access. As indicated by the research results, while conventional farming generated higher crop yield (e.g., the wheat crop: 4.47 vs. 3.82 t/ha, $p = 0.034$), organic farming improved in terms of resource utilisation, using less water (130.4 vs. 160.2 m3/t, $p = 0.03$) and energy consumption (225.6 vs. 270.8 kWh/t, $p = 0.02$). Organic farming was associated with better soil health (organic farming: 3.8% vs. 2.9%, $p = 0.005$) and superior biological diversity (species richness: 25 vs. 15, $p = 0.008$). Both findings were considered statistically significant. In terms of the marketplace, 68.2% of organic farming were able to access top marketplaces, whereas only 40.5% of conventional farming were ($p = 0.01$). By doing this, these individuals were able to negotiate higher costs (₹75.6 vs. ₹63.4/kg, $p = 0.02$). There is a clear result that organic farming products can be successful globally, as shown by the revealed comparative advantage (1.53).

Keywords: Organic Farming Practices; Agricultural Productivity; Market Access; Revealed Comparative Advantage; Soil Health; Machine Learning

1. Introduction

Conventional farming poses risks to the natural environment, human health, and economic growth, and organic farming is increasingly understood as an acceptable alternative [1]. As a sustainable substitute to traditional agricultural methods that rely on chemical fertilisers, pesticides, and intensive cultivation, Organic farming supports the conservation of natural resources, biological diversity, and soil health [2]. Studying the full range of organic farming's effects on society, including agricultural efficiency, environmental sustainability, and market competitiveness, is becoming increasingly important for researchers, policymakers, and farmers as global demand for organic products grows [3].

The potential of organic farming to enhance sustainable agriculture while minimising environmental degradation has gained increased significance in several regions, including India [4]. As one of the world's most prolific agricultural producers, India plays a significant role in the overall organic farming metric [5]. The distinct agro-climatic zones of the nation and the growing responsiveness to the benefits of organic food have all played an integral role in the recent development of Organic Farming [6]. The economic practicality, productivity, and profitability of organic compared to conventional farming remain under review, despite its clear advantages [7].

Agricultural productivity, sustainable development, and economic competitiveness are among the essential agricultural outcomes the present investigation seeks to assess in relation to organic farming practices. Research evaluates the variances and resemblances between organic farming and conventional farming in the fields of resource utilisation, crop quality, carbon footprint (tCO_2), biological diversity, and crop yield per hectare (metric tons per hectare, t/ha) [8].

Furthermore, the research uses revealed comparative advantage analysis to determine organic farming's export capacity and focuses on the organisation's ability to penetrate top markets and negotiate higher prices [9]. The current study focuses on the impact of Organic Farming on agricultural productivity, environmental sustainability, and business relations in the Indian state of Punjab, one of the most productive farming regions in India. The proposed research incorporates empirical, economic analysis, and qualitative methods to compare organic and conventional farming and highlight the general significance of organic farming for sustainable agriculture development [10].

In response to the economic, environmental, and soil health problems conventional farming faces, a novel form of farming has emerged: organic farming. There has been environmental degradation, an overall decrease in Soil health, and a loss of biological diversity resulting from conventional farming's high crop yield, enabled by chemical fertilisation, pesticide application, and agricultural practices. One feasible solution to these problems is organic farming, which focuses on the state of biological diversity and organic inputs. The contrast between the economic benefits of organic and conventional farming, their level of efficiency, and their market edge are all points of conflict [11].

There's no systematic analysis of organic farming's impact on sustainable environments, food security, or the economic viability of states like Punjab in India, which has been recognised as an agriculturally dominant force. Since organic farming has the promise of improving Soil Health, reducing carbon footprints, and addressing other negative environmental impacts, there has been a lack of research that thoroughly assesses its impact on crop yield, resource utilisation, the economy, and market access. Also, there is a limitation to the analysis of the impacts of organic and conventional farming on productivity and business profitability, especially in historically essential and strategically complex agricultural regions such as the province of Punjab [12].

Furthermore, additional analysis is required because there is no data source on organic farming products linked to global competitiveness metrics, such as revealed comparative advantage. To address these gaps, the present investigation evaluated organic and conventional farming in Punjab using key parameters including crop yield per hectare, resource utilisation, soil health, biological diversity, carbon footprint, and market access [13]. While conventional farming yields better overall results, Organic Farming surpasses it when accounting for financial resources, environmental impact, and market share. To provide just a few examples, organic farming increases costs in high-value markets while reducing water and energy use, enhancing soil health and species richness, and securing these markets for future generations. The additional use of root cause analysis further verifies that organic farming products are ahead of the competition globally. Hence, essential stakeholders in the agricultural value chain and policymakers may apply the results of this study to inform significant decisions on sustainable agricultural practices [14].

To achieve high crop yield without affecting the natural environment, sustainable agriculture is essential. When farmers use sustainable farming methods that rely on only a few chemical fertilisers, the soil becomes more fertile, the adverse environmental impacts are reduced, and biological diversity is preserved [15].

Modern industrial agricultural practices, including the use of chemical-based fertilisers and pesticides, lead to higher crop yields but also cause resource waste and polluted environments. Previous research has emphasised the positive impacts of organic farming on maintaining ecological balance by improving consumer wellbeing. On the other hand, they show problems such as decreased productivity and higher wages.

The present investigation contributes to the existing research system by systematically analysing differences between organic and conventional farming in the Punjab state of India, a region heavily impacted by the Green Revolution and intensive farming practices [16]. Research like this helps fill a significant gap in the literature by providing new statistical indicators for sustainability, competitiveness, and productivity in developing nations like India, which depend substantially on agriculture for their financial systems and ecological balance [17].

To provide knowledge about sustainable agriculture, this research observes the advantages and disadvantages of organic and conventional farming. The research results further validate that organic farming could contribute to environmentally friendly business performance and to improved resource utilisation [18].

Organic farming improved soil health, decreased total carbon footprint, increased biological diversity, and helped create a more acceptable marketplace at a higher cost, according to organic farming. While the crop yield may be lower than that of organic farming, the harvest is of higher quality, more economically feasible, and closer to meeting global sustainability standards for agriculture. For policymakers, these are significant advantages that should motivate sustainable agriculture and farmers to adopt sustainable methods. In addition to resolving the crop yield gap, the study provides the basis for accurate farming and the practical application of organic farming. The revealed comparative advantage results show that organic farming products are really global, which bodes well for their trade prospects and supports organic farming as a sustainable agriculture model [19].

The primary goals of the research project include the following:

1. This evaluation aims to compare resource use and crop yield levels between organic and conventional farming.
2. To determine the impact that organic farming has on soil health, biological diversity, and carbon footprint levels.
3. To determine the market access, high cost, and export probability of products produced by organic farming.

The outline that follows summarises the study: Section 3 focuses on the methodology, Section 4 addresses the analysis, and Section 5 concludes the research paper.

2. Related Works

Seufert et al. (2012)[20] conducted a global meta-analysis of conventional and organic farming. The results differed by crop type and sustainable agricultural practices, but in general, organic farming yields 25% less than conventional farming. Improved sustainable agricultural practices must be implemented for organic farming to fully meet global food demands, even though it improves soil health, biodiversity, and resource utilisation. The research highlights the challenges that farming practices face when seeking to reconcile productivity with ecological sustainability.

A meta-analysis by Ponisio et al. (2015)[21] examined the probability that organic farming practices, such as crop rotation, intercropping, and multiple-crop cultivation, would reduce yield mismatches compared to conventional farming. Heterogeneous organic farming improved soil health, biodiversity, and nutrient cycling, and substantially reduced the yield gap, particularly for peanuts and corn crops, according to the study. To achieve sustainability and higher profits, research suggests that organic farming is not a cost but a productivity-enhancing practice. Instead, improved management methods are key to achieving more productive, sustainable agriculture.

Pretty et al. (2018)[22] have analysed the impacts of sustainable methods in numerous countries and agricultural methods. The organisation is resolute that sustainable agricultural practices, such as integrated water and soil management, reduce chemical use, improve crop management, increase resource utilisation and crop yields, particularly for smallholder farmers, and positively impact the environment. Sustainable agricultural practices can enhance food security, rural incomes, and the environment, according to the research report. However, there is still no comprehensive method in place to study the complete impacts of climate change.

The research[23] investigated how smallholder farmers in Africa employ climate-smart agriculture methods. According to the research, climate-smart agriculture practices, including water usage, soil health, and growing drought-tolerant crops, work together to develop farms that are less susceptible to damage, increase technical productivity, and reduce yield losses resulting from climate change. Although the study found that climate-smart agriculture adoption improved crop yield in rural regions under climate stress, the economic improvements were context-specific and could not be generalized to other regions.

Soil health, carbon sequestration, and climate adaptation are among the primary fields of emphasis in Lal et al. (2022)[24], which are centred on organic and sustainable farming practices. This shows that organic farming, cover crops, and no-till farming work together to produce more fertile soil, which, in turn, increases carbon storage and reduces greenhouse gas emissions, helping keep the planet sustainable. There is an essential requirement for supplementary reviews of the multiple impacts of sustainable agricultural practices, since although these practices improve environmental results, research seldom measures short-term profitability or farm-level productivity.

A global study by Campbell et al. (2021)[25] investigated viable intensification methods and climate-smart agriculture in numerous locations. The study they conducted provides proof that climate-smart agriculture can increase crop yield, build resilience to climate change, and reduce greenhouse gas emissions—a "triple win," in their words. Soil conservation, integrated water use, and improved crop management are some of the tactics they emphasise. But empirical testing at the farm level is lacking, and most research is theoretical or model-based, so we don't fully understand the real-world efficiency and economic outcomes.

Smith et al. (2014)[26] analysed the global environmental benefits of agriculture using life-cycle assessments and modelling. Researchers determined that agricultural forestry, reduced cultivation, improved nutrient management, soil carbon storage, and other similar methods may significantly reduce greenhouse gas emissions without reducing or even increasing crop yields. Also, there needs to be more targeted evaluation of sustainable farming measures at the regional level, as these research investigations focus primarily on climate sustainability without exploring the financial implications for agriculture or rural efficiency.

When comparing organic to conventional farming, Gomiero (2018)[27] assessed how it impacts the ecosystem. Organic methods, according to the research, improve water quality, biodiversity, and soil health while reducing chemical pollution. On the other hand, there may not be sufficient crops because organic farming typically yields lower per-unit-area yields. Although the beneficial impacts on the natural environment are evident, there is a lack of research that combines productivity, sustainability, and economic results, as the study primarily emphasises environmental benefits without investigating economic performance at the farm level.

In a global meta-analysis, Crowder and Reganold (2015)[28] compared the economic performance of conventional and organic farming methods. Despite usually lower yields, they found that organic farms are frequently 22–35% more profitable due to high prices for organic products. While the study validates that organic farming can be profitable and good, it does little to assess the environmental impact or technical efficiency of the practice, beyond how much money it generates.

In the study of renewing vs. conventional farming methods, Jaffry et al. (2004)[29] compared their economic performance. The research they conducted verified that regenerative farms are frequently more economically viable than conventional farms in the long term due to lower input costs, improved soil health, and greater resilience to climate change. There is room for an integrated analysis of multiple benefits, because although the research emphasises sustainable GDP growth, it provides only a limited evaluation of the effective functioning of rural agriculture or the impacts of climate mitigation.

Barrett et al. (2025)[30] have examined the impact of sustainable agricultural practices on farmers' profitability and adaptability. Sustainable practices reduce income volatility, increase food security, and make populations less susceptible to extreme weather events, according to the research study. However, the report provides limited proof of farm-level efficiency and environmental impacts, suggesting the limitations in integrating economic efficiency and climate sustainability outcomes in rural agriculture.

Table 1 summarizes the conclusions of several research studies conducted over the last two decades that compared organic and conventional farming. Agricultural economics, environmental changes, and agricultural practices are all addressed in the research literature, and many meta-analyses have collected data at the global level. Organic farming is said to have lower yields but improved environmental results; however, performance may differ significantly depending on the crop being grown, the region, and the level of management. For an accurate assessment, this study must include benchmark analyses of soil health, biodiversity, profitability, climate impacts, and socioeconomic factors.

Table 1. Summary of Related Works.

Focus of Study	Methodology	Key Findings	Limitations
Organic vs. Conventional Crop Yield[31]	Meta-analysis	An organic framing method to improve soil health and biodiversity, but crop yield is 15–30% less.	Focused mainly on yields, limited climate changes, and profit
Crop Yield Analysis of Organic Methods[32]	Meta-analysis	Crop yield gap reduced with differentiated practices; better resource-use efficiency.	No analysis of climate mitigation or economic profit
Sustainable Increase in Developing Countries[33]	Longitudinal multi-country study	Sustainable agricultural practices improve crop yield.	Limited climate impact quantification

Table 1. *Cont.*

Focus of Study	Methodology	Key Findings	Limitations
Climate-Smart Agriculture Adoption [34]	Farm-level studies; productivity models	Climate-smart agriculture increases technical competence and reduces climate susceptibility.	Region-specific; limited profit analysis
Soil Carbon and Renewing Agriculture [35]	Experimental soil science studies	Conservation agriculture greatly increases soil carbon and adaptability to climate change.	Does not assess farmer economics
Climate-Smart Agriculture [14]	Theoretical and classification analysis	Finds "triple win": productivity, adaptation, mitigation.	Limited experimental testing in rural people
Global Mitigation of Agriculture [36]	Global Life Cycle Assessment and Modelling	Agriculture proposals significant inventions for reducing soil carbon and reducing inputs.	No micro-level rural livelihood impacts
Environmental Impacts of Organic Methods [37]	Literature analysis	Strong biodiversity and soil benefits; low chemical pollution.	Limited profit and efficiency assessments
Profitability of Organic Farming [38]	Meta-analysis	Organic farms are 22–35% more profitable due to rewards.	Limited climate system of measurement; short-term motivation
Economic Sustainability of Regenerative Methods [39]	Field economic value	Regenerative farms outperform conventional farming long-term.	Limited assessment of rural productivity
Rural Markets & Sustainable Agricultural Adoption [40]	Agricultural GDP growth	Sustainable agricultural practices reduce income unpredictability and improve adoptability.	Does not quantify climate mitigation impacts

And also below, **Table 2** is mentioned as a contrast between organic and conventional farming methods.

Table 2. Primary Data Comparison of Organic and Conventional Farming in Punjab.

Indicator	Organic Farmers* (n = 29)	Conventional Farmers* (n = 30)
Average Farm Size (ha)	1.42	1.55
Soil Organic Carbon (%)	0.89	0.62
NPK Chemical Fertilizer Use (kg/ha)	12.4	148.7
Compost/Vermicompost Use (t/ha)	3.1	0.4
Pesticide Use (L or kg/ha)	0.8	4.9
Average Yield (kg/ha)	3,020	3,420
Cost of Cultivation (INR/ha)	41,600	58,300
Gross Income (INR/ha)	78,300	80,950
Net Income (INR/ha)	36,700	22,650
Benefit–Cost Ratio	1.88	1.39
Water Use (m^3/ha)	4,800	5,500
Soil pH	6.7	6.3
Farmers Reporting Improved Soil Structure (%)	82%	34%
Farmers Reporting Pest Incidence Reduction (%)	71%	22%
CO_2-eq Emissions (kg/ha/year)	1,140	2,780
Farmer Satisfaction Level (1–5 Likert)	4.2	3.5

Note: *A total of 59 farms have been considered for test sampling methods.
Source: Author-collected field data [41, 42].

3. Methods

3.1. Study Area and Sampling

Punjab, a central state in India's agricultural sector, was selected as the research project's location (**Figure 1**). The fertile soils and resourceful irrigation methods of Punjab have historically contributed significantly to India's agricultural production. The region is attracting increasing attention in organic farming due to the environmental risks posed by conventional farming's chemical-based sustainability agriculture practices. Punjab provides an ideal environment for the present study, as it is advancing towards organic farming to address problems related to soil health, biological diversity, and safe resource utilisation.

Figure 1. Punjab State Map.

Ludhiana, Patiala, and Amritsar are the three primary rural districts under focus in the current study. The many farming methods and crop types in the above regions were key factors in their selections. The percentage of small conventional farming has been greater in Amritsar; however, Ludhiana has become known for its mechanised, massive agricultural practices.

A total of 59 farms, involving 29 organic and 30 conventional farms, were selected for the study. Organic farming was selected from a list of certified farms by the Punjab Organic Certification Authority, with a minimum of 5 years of organic farming experience. Conventional Farming was identified based on its reliance on chemical inputs. This sampling method was designed to provide a balanced illustration of the region's farmland without an even split among farm types [43].

The study sampling methods (n = 59 farms; 29 organic, 30 conventional) and one year of records limit statistical power to detect small/moderate effects and do not allow extrapolation to medium/long-term trends (e.g., soil organic matter trends, multi-year crop yield stability). The sampling frame, which will be based on certified organic registries and closely follow conventional procedures, may introduce selection biases (e.g., adopter heterogeneity and management strength) that cannot be corrected by cross-sectional covariate adjustment. This study recommends (i) the analyses to identify minimum detectable effect sizes to use in future studies, (ii) panel designs with repeated measures to account for temporal autocorrelation and trend effects, and (iii) probabilistic sampling or propensity-score designs to decrease selection bias and increase cause attribution [42].

The study period spans the agricultural year from January to December 2023, enabling the research to capture data across the major cropping seasons—rabi (winter) and kharif (summer). The selected time frame accounts for the periodic nature of many crops, including staples like wheat, rice, and maize, as well as high-demand crops like fruits and vegetables. Different types of economic inputs were measured when reviewing each farming operation to ensure the investigation encompasses a range of organic farming scales, from conventional farming to farms integrated into international and regional trade networks [44].

3.2. Data Collection Methods

Using the province of Punjab as a case study, the present study aims to assess organic and conventional farming practices in terms of crop yield (CY), environmental impact, and financial sustainability. By comparing several performance metrics, including CY, resource utilisation, environmental impacts, and market access, this research systematically analyses the trade-offs between the two farming methods [45]. Problems such as low productivity in organic farming are being addressed, and global trade opportunities for organic farming products are being recognised using tools such as the revealed comparative advantage. The research compares resource-intensive methods in conventional farming with environmentally conscious methods, using sustainable agriculture models to measure positive environmental outcomes, such as improved soil health and reduced carbon footprint. To achieve long-term financial and ecological objectives in agriculturally impacted districts, the research provides decision-makers, farmers, and other participants with data on sustainable agriculture, particularly regarding organic farming as a probable alternative to conventional farming.

To guarantee that organic-conventional farming comparison illustrations actual variation in farming systems and not sampling things, the sample of farms was selected and balanced on a fixed number of physical and contextual covariates. It started its selection using the registry and field frame (certified organic lists and district agricultural rolls) and stratified sampling by district and primary crop to maintain the agro-ecological and crop-mix structure of the study area. Screening of candidate farms was conducted based on the levels of farm size (hectares—ha), dominant crop type (cereals, oilseeds, and horticulture), irrigation (canal, tube-well, and rainfed), set of mechanisation (kWh/ha), market orientation (local/regional/export), and its location (km). Farmer socio-demographics (age, years of farming experience, level of formal training, and household labour availability) and management measures (years converted to organic, certification, and previous yield history) were directly collected and used as balancing variables. At the analysis level we have used propensity-score matching (nearest neighbour, caliper = 0.1) and inverse-probability weighting to form counterfactual groups, and have evaluated covariate balance by standardized mean changes (target SMD < 0.10) and t-tests on selected key continuous variables; where imbalance remained this study used those covariates as controls in regression models and conducted sensitivity analysis (Rosenbaum bounds and placebo results). Lastly, robustness analyses, such as exact matches on crop class and district, stratified regressions based on farm-size tertiles, and bootstrap confidence intervals, ensured that the productivity factors associated with resource use and environmental changes are not affected by clear selection bias but by systematic differences related to the production system.

3.2.1. Agricultural Productivity

Metrics such as crop yield per hectare, soil health, and resource utilisation were used to assess farm profitability. Productivity data have been collected directly from farmers' diaries, which record agricultural area, crop type, and rabi and kharif crop yield. To ensure the accuracy of the self-reported crop yield data, field visits were conducted [46]. In addition to measuring crop yield, researchers assessed crop quality by collecting samples from each location and analysing them for factors such as moisture levels, pest and disease susceptibility, and nutritional value. This study identified the potentially higher cost of organic products by comparing crop quality metrics with market prices. To measure resource utilisation, researchers also recorded input data, including irrigation water consumed and fertiliser type (organic or conventional). To compare the success rates of organic and conventional farming in producing crop yields, the input-output ratio was determined for each agricultural operation.

3.2.2. Environmental Sustainability

With a focus on soil health, biological diversity, and tCO_2 analysis, environmental sustainability has been assessed through an integrated method. To conduct Soil Health tests, soil samples have been obtained from each farm and provided to certified laboratories for testing. Microbial activity, pH, nutrient levels (nitrogen, phosphorus, and potassium), and organic matter content were observed in the samples. The use of sustainable organic farming methods in maintaining soil fertility over the long term has been assessed using these indicators of success. This work also developed biological diversity indices by describing the different plant, insect, and animal species identified on the farms by real-time surveys. Because organic farms did not use chemical fertilisers or pesticides, it was predictable that they would have higher levels of biological diversity. To determine the value of greenhouse gas emissions from each farm, a tCO_2 analysis was performed. Maintaining control over the farm's energy consumption, the transportation of inputs and outputs, and the use of petroleum and natural gas in agricultural equipment was integral to this study and is a focus of it. This work has determined the carbon footprint emissions associated with distributing organic and conventional farming products to regional and local marketplaces using data on transportation distances.

3.2.3. Trade Competitiveness

This study identified the farmer's business competitiveness by systematically analysing each farm's market involvement. The value of agricultural produce sold in local, regional, and export markets was identified by interviews with farmers, who provided market data. Determining average market prices for different crops and whether farmers received higher prices for organic farming products was part of the research. To compare the organic and conventional farming in terms of their development into high-value markets, market share data was compiled by examining farm records and sales receipts. The number of organic products imported from Punjab to international markets was tracked using export-import data collected from government trade databases and local agricultural marketing boards. This work compared these numbers with the export volumes recorded by farmers to determine if Organic Farming had a viable advantage over conventional farming products in export markets. This analysis provided clarification on the financial sustainability of organic farming in domestic and global trade contexts (**Table 3**).

Table 3. A Summary of the Data Collected, Units, and Sources.

Metric	Unit	Source
Crop Yield per Hectare	Metric Tons/Hectare (t/ha)	Farm records and field visits
Crop Quality (Nutritional Content)	Percentage (%)	Laboratory tests and market prices
Soil Organic Matter	Percentage (%)	Soil sample laboratory tests
Soil Nutrient Levels (N, P, K)	mg/kg	Soil sample laboratory tests
Soil pH	pH scale	Soil sample laboratory tests
Biological Diversity Index (Species Richness)	Count of species	On-site biological diversity surveys
Carbon Footprint	kg CO_2 equivalent (kg CO_2-eq)	Fuel and energy consumption records
Market Price (Organic)	₹/kg	Farmer interviews and market surveys
Market Price (Conventional Farming)	₹/kg	Farmer interviews and market surveys
Volume Exported (Organic Farming)	Metric Tons (t)	Export records and farmer data
Volume Exported (Conventional Farming)	Metric Tons (t)	Export records and farmer data
Water Usage	Cubic Meters (m^3)	Farm records and irrigation logs
Energy Consumption	Kilowatt Hours (kWh)	Farm records and energy bills

3.3. Analytical Model

This study's analytical model integrates quantitative, qualitative, and economic statistical approaches to examine how organic farming practices impact agricultural productivity, sustainable development, and trade competitiveness.

3.3.1. Agricultural Productivity Analysis

Using qualitative data, the present investigation provides the average and standard deviation of primary productivity metrics, such as crop yield per hectare and crop quality, to assess organic and conventional farming relative to crop yield.

The formula for the mean is Equation (1).

$$\text{Mean}(\mu) = \frac{\sum X}{n} \tag{1}$$

where X is the individual crop yield or crop quality value, and n is the number of farms sampled.

Following this work, apply a two-sample *t*-test to find whether the differences in crop yield and crop quality between organic and conventional farming are statistically significant. The *t*-test compares the means of two groups and tests the null hypothesis that there is no significant difference between them.

The Equation (2) for the *t*-test is:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \tag{2}$$

where $\bar{X}_1$ and $\bar{X}_2$ are the mean organic and conventional farming as s_1^2 and s_2^2 are the variances and n_1 and n_2 are the sample sizes. To analyze resource utilisation (water usage and energy consumption), this study employs Data Envelopment Analysis, which measures the efficiency of multiple decision-making units (in this case, farms). Data envelopment analysis compares inputs (water and energy) to outputs to determine how efficiently each farm utilises its resources[35].

The efficiency score is calculated as Equation (3).

$$\text{Efficiency} = \frac{\text{Weighted Sum of Outputs}}{\text{Weighted Sum of Inputs}} \tag{3}$$

This method allows us to identify whether organic farming is more resource-efficient than conventional farming.

Environmental Sustainability (ES) Analysis: Several statistical methods are used to analyse ES. This work first employs multiple regression analysis to investigate the relationship between farming practices (Organic/Conventional) and Soil Health indicators, including organic matter content and nutrient levels.

The general form of the regression model is Equation (4):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k + \epsilon \tag{4}$$

where Y is the dependent variable (e.g., organic), β_0 is the intercept, $\beta_1, \beta_2, \ldots, \beta_k$ are the coefficients for the independent variables $X_1, X_2, \ldots, X_k$ (e.g., farm type, crop type, and farm size), and ϵ is the error term.

To assess biological diversity, this work uses the Shannon-Wiener Index ($H^{'}$) to quantify biological diversity on the farms.

This index measures species richness and evenness and is calculated as Equation (5):

$$H^{'} = -\sum (p_i \ln p_i) \tag{5}$$

where p_i is the proportion of each species relative to the sum of the species experienced. A higher $H^{'}$ the value indicates more extraordinary biological diversity. To determine whether the results indicate a significant difference in biological diversity between organic and conventional farming, the present study employs a Multivariate Analysis of Variance (MANOVA).

To assess the carbon footprint, this research conducts a life-cycle assessment to calculate total greenhouse gas emissions for each farm. The life cycle assessment assesses the emissions from inputs (fertilisers and fuels) to outputs (crops harvested and transported).

The carbon footprint is expressed as Equation (6).

$$\begin{gathered}\text{carbon footprint} = \\ \sum (\text{CO}_2 \text{ emissions per unit of input})\end{gathered} \tag{6}$$

This provides a comparison of the environmental impacts between organic and conventional farming.

3.3.2. Trade Competitiveness Analysis

For trade competitiveness, this study employs logistic regression to analyze the factors influencing whether organic farming can access premium markets. The dependent variable is whether a farm has access to high-value markets (1 if yes, 0 if no), and the independent variables include farm size, crop type, and certification status.

The logistic regression Equation (7) is:

$$\ln\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k \quad (7)$$

where p is the probability of accessing a premium market, and $X_1, X_2, \ldots, X_k$ are the independent variables affecting that probability. To evaluate the competitiveness of organic products in export markets, this study uses the revealed comparative advantage index, computed as shown in Equation (8):

$$RCA = \frac{(X_{\text{organic}}/X_{\text{total}})}{(X_{\text{world\_organic}}/X_{\text{world\_total}})} \quad (8)$$

where X_{organic} is the export value for the organic farming products from Punjab, X_{total} is the total export value, and $X_{\text{world\_organic}}$ and $X_{\text{world\_total}}$ are the corresponding global values. Organically grown products have a relative advantage when the revealed comparative advantage exceeds 1.

4. Result Analysis

4.1. Analysis of Agricultural Productivity

Table 4 indicates that, across all crops, conventional farming yields per hectare are higher than those of organic farming, as shown in the crop yield study in **Figure 2**. In contrast, the wheat crop yield was 3.82 t/ha in organic farming, compared with 4.47 t/ha in conventional farming (p = 0.034). Similarly, conventional vegetable farms yielded 17.80, 4.98, and 3.97 t/ha, while organic farming yielded only 4.23, 3.12, and 15.30 t/ha. The yield differences across all crops are statistically significant. **Table 4** highlights the differences in crop quality. Organic products proved higher nutritional content, with organic farming crops having an average protein content of 12.4% compared to 11.1% for conventional farming crops (p = 0.02). Organic farming crops also exhibited better pest resistance (4.3 vs. 3.8), longer shelf life (12.8 vs. 9.5 days), and higher market prices (₹75.6 vs. ₹63.4/kg). These differences are statistically significant across all metrics.

Despite several crop classes being identified, the empirical focus and most reported statistical tests are based mainly on staple cereals (e.g., wheat), limiting the ability to infer other crop functional groups (e.g., legumes, oilseeds, and horticulture). The input-crop yield and crop-specific physiological responses to organic farming, along with contrasting productivity and efficiency, imply that productivity and efficiency cannot be similarly transferred among crops. We thus condition the proposed findings on the crop yield gap and resource utilisation provisions as measured, which are mostly indicative of the sampled crop portfolio in Punjab in the 2023 production year (**Table 5**). Future research should use stratified sampling of demonstrative crop guilds and employ crop-level fixed effects or crop-management interaction terms to obtain more detailed and generalizable estimates.

The resource utilisation data, presented in **Table 6**, indicate that organic farming generally uses fewer inputs per output unit. Organic farming used less water (130.4 vs. 160.2 m^3/t, p = 0.03) and energy (225.6 vs. 270.8 kWh/t, p = 0.02) than conventional farming. Labour input was also lower on organic farms (45.3 vs. 52.1 person-h/t, p = 0.04). Fertiliser and pesticide use were significantly lower in organic farming, with organic farming using no pesticides and 80.5 kg/t of fertiliser, compared to 105.8 kg/t in Conventional Farming. Land use efficiency was better on organic farming (0.25 vs. 0.3 ha/t, p = 0.03), and capital investment per ton was also lower (₹1,250.7 vs. ₹1,350.9, p = 0.02). The Data Envelopment Analysis efficiency results in **Table 7** show that organic farming had a higher mean Data Envelopment Analysis efficiency score (0.87) than conventional (0.74), and organic farming also demonstrated greater consistency, with a narrower range between the minimum and maximum efficiency scores (0.72 to 0.99) than conventional (0.58 to 0.89).

4.2. Analysis of Environmental Sustainability (ES)

The results for environmental sustainability are shown in **Figure 3**, and the soil health analysis presented in **Table 8** shows that organic farming had significantly better soil health metrics across all types. Organic farming had higher levels of organic matter (3.8% vs. 2.9%, p = 0.005), nitrogen (50.4 vs. 42.7 mg/kg, p = 0.027), phosphorus (35.2 vs. 28.4 mg/kg, p = 0.041), and potassium (180.1 vs. 150.3 mg/kg, p = 0.012). Soil pH was lower in organic farming (6.8 vs. 7.3, p = 0.048), indicating superior suitability for crop yield.

Table 4. Analysis of Crop Yield per Hectare.

Crop	Organic-Crop Yield (t/ha)	Conventional-Crop Yield (t/ha)	*p*-Value (*t*-Test)
Wheat	3.82	4.47	0.034
Rice	4.23	4.98	0.022
Maize	3.12	3.97	0.015
Vegetables	15.30	17.80	0.043

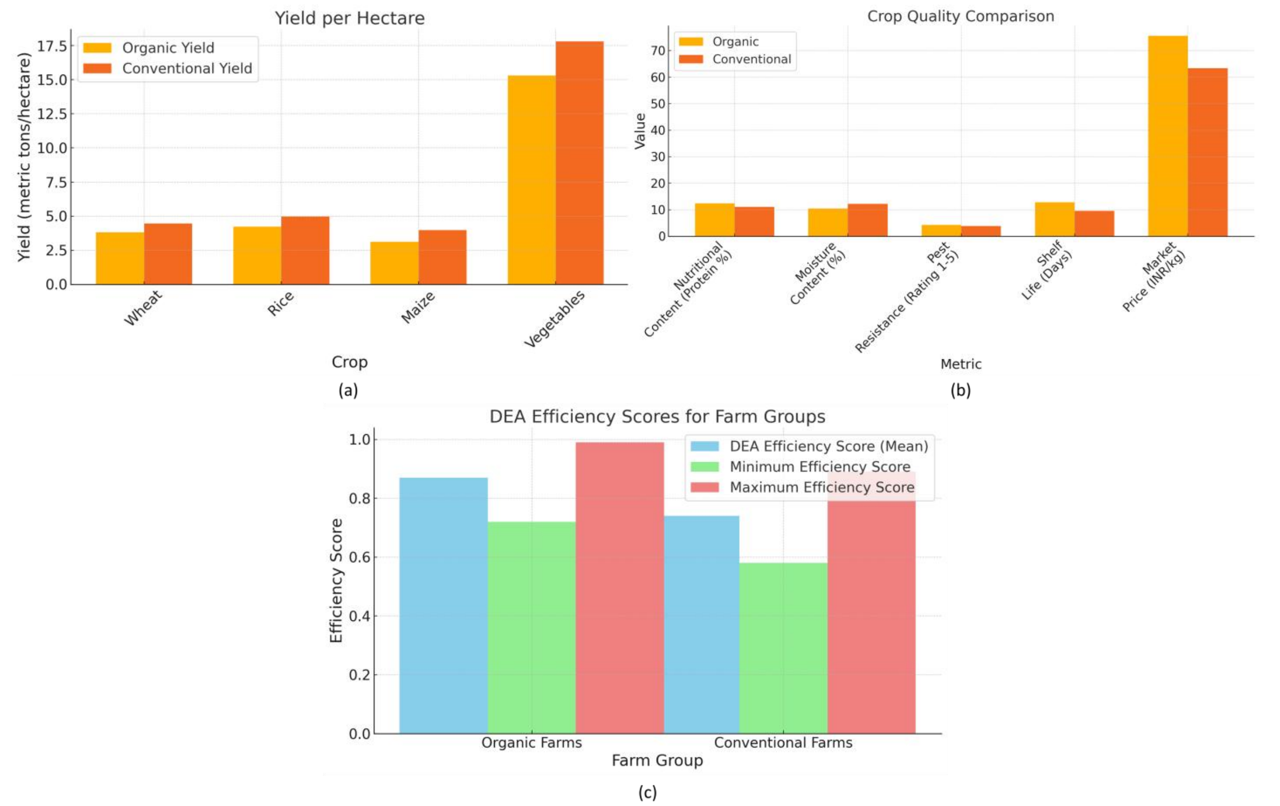

Figure 2. Agricultural Productivity Results.

Table 5. Analysis of Crop Quality.

Metric	Organic	Conventional	*p*-Value (*t*-Test)
Nutritional Content (Protein %)	12.4	11.1	0.02
Moisture Content (%)	10.5	12.2	0.03
Pest Resistance (Rating 1–5)	4.3	3.8	0.04
Shelf Life (Days)	12.8	9.5	0.01
Market Price (₹/kg)	75.6	63.4	0.02

Table 6. Analysis of Resource Utilisation.

Metric	Organic	Conventional	*p*-Value (*t*-Test)
Water Usage (m^3/t)	130.4	160.2	0.03
Energy Consumption (kWh/t)	225.6	270.8	0.02
Labor Input (person-h/t)	45.3	52.1	0.04

Table 6. *Cont.*

Metric	Organic	Conventional	*p*-Value (*t*-Test)
Fertilizer Use (kg/t)	80.5	105.8	0.01
Pesticide Use (kg/t)	0.0	10.7	N/A
Land Use Efficiency (ha/t)	0.25	0.3	0.03
Capital Investment (₹/t)	1,250.7	1,350.9	0.02

Table 7. Data Envelopment Analysis.

Farm Group	Number of Farms	Data Envelopment Analysis Efficiency Score (Mean)	Minimum Efficiency Score	Maximum Efficiency Score
Organic	29	0.87	0.72	0.99
Conventional	30	0.74	0.58	0.89

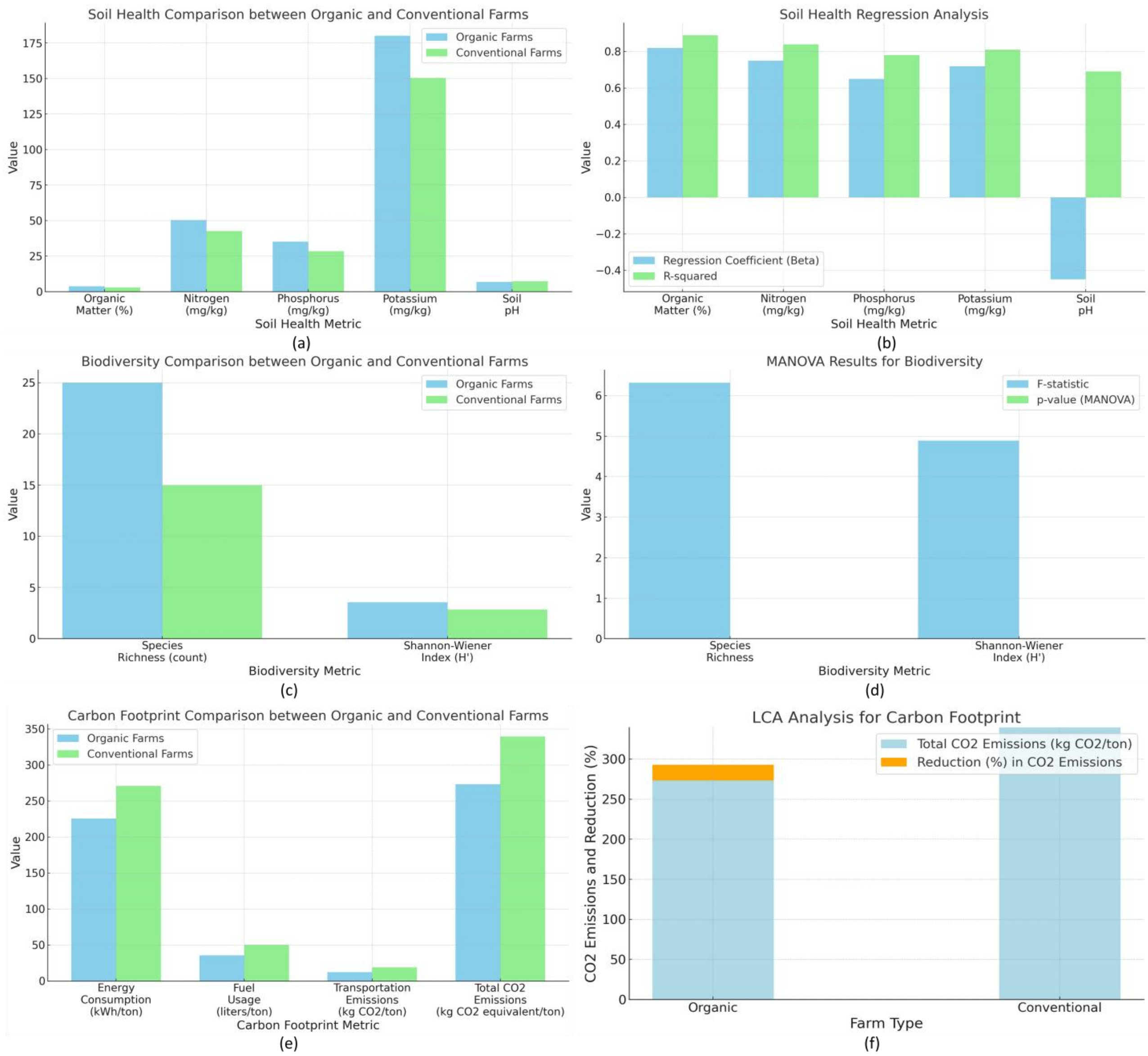

Figure 3. ES Results.

Table 8. Comparison of Soil Health.

Soil Health Metric	Organic	Conventional	*p*-Value (*t*-Test)
Organic Material (%)	3.8	2.9	0.005
Nitrogen (mg/kg)	50.4	42.7	0.027
Phosphorus (mg/kg)	35.2	28.4	0.041
Potassium (mg/kg)	180.1	150.3	0.012
Soil pH	6.8	7.3	0.048

Table 9 presents the findings of a regression analysis of soil health, indicating a positive correlation between organic farming practices and improved soil health. The organic farming exhibited a significant correlation with an R-squared value of 0.89 and a reliable high regression coefficient ($\beta = 0.82$, $p = 0.01$). The relationships between nitrogen, phosphorus, and potassium were highly positive ($\beta = 0.75$, 0.65, and 0.72), and the *p*-values were significant. The slope of the soil pH statistic was negative ($\beta = -0.45$, $p = 0.05$), indicating that soil pH is lower in organic farming than in conventional farming.

Table 9. Regression Analysis of Soil Health.

Soil Health Metric	Regression Coefficient (Beta)	R-Squared	*p*-Value (Regression)
Organic Material (%)	0.82	0.89	0.01
Nitrogen (mg/kg)	0.75	0.84	0.02
Phosphorus (mg/kg)	0.65	0.78	0.03
Potassium (mg/kg)	0.72	0.81	0.01
Soil pH	−0.45	0.69	0.05

Table 10 presents the results of the biological diversity analysis, indicating that the organic farming maintained a Shannon-Wiener Index (H' = 3.54) and had significantly higher species richness than the other group (25 vs. 15 species, $p = 0.008$). The biological diversity of species ($F = 6.32$, $p = 0.005$) and the Shannon-Wiener Index ($F = 4.89$, $p = 0.009$) were substantially distinct between organic and conventional farming, as illustrated in **Table 11** and verified by MANOVA results.

According to **Table 12**, the carbon footprint in organic farming has been significantly reduced. Organic farming consumed less energy (225.6 vs. 270.8 kWh/t, $p = 0.015$), used less fuel (35.4 vs. 50.2 L/t, $p = 0.01$), and emitted fewer transportation-related CO_2 emissions (12.3 vs. 18.7 kg CO_2/t, $p = 0.02$). Assuming a *p*-value of 0.005, CO_2 emissions from organic farming were 273.3 kg CO_2-eq, while emissions from conventional farming were 339.7 kg. The life cycle assessment analysis in **Table 13** indicates that organic farming reduces total CO_2 emissions by 19.55% compared to conventional farming, further reinforcing the environmental benefits of the organic farming practices. The Organic Farming emitted 273.3 kg CO_2-eq, while conventional farming emitted 339.7 kg CO_2-eq.

This study operationalises an edge-deployed Artificial Intelligence pipeline for crop recommendations by fusing real-time soil-sensing and weather data. Methodologically, the paper contributes an applied architecture: multi-sensor soil telemetry (RS485 7-in-1 sensor), a weather Application Programming Interface, an Internet of Things and dashboard (ThingsBoard), and on-device inference on a Raspberry Pi 5. The dataset (n = 3300; 22 crops; 8 features) supports supervised classification experiments comparing ensemble tree methods (Random Forest, Gradient Boosting, stacking ensembles) and a tabular deep model (TabNet). The authors report high classifier accuracies (Random Forest ≈ 95.8%, stacking ≈ 95.9%, and TabNet ≈ 92%) and prioritise Random Forest for inference due to its lower latency and TFLite compatibility. A practicality analysis is additionally performed among stakeholders, and explainable artificial intelligence has been included to enhance accessibility.

The proposed Internet of Things-enabled sustainability agriculture project, an Internet of Things-based crop modelling system, and an internet-based agriculture review are all models employed in agricultural research. **Figure 4** provides an overview of these models across 7 core quantitative features. Environment-related metrics and economic/market access metrics, supported by robust quantitative methodologies such as data envelopment analysis, life cycle assessment, and revealed comparative advantage, validate the highest overall performance in the proposed research, as shown in **Figure 4**. With its real-time data collection and edge-deployed predictive model, the Internet of Things-enabled crop prediction network discerns itself by its design and Machine Learning integration. The digital agriculture study, on the other hand, is significantly ahead of the competition because of its detailed overview of emerging digital agriculture applications worldwide. Presented as an ensemble, the visualisation emphasises the mutual support of the three methodologies used in research, indicating how next-generation sustainability agriculture and precision systems can be improved by combining the features of theoretical digital agricultural summaries, empirical sustainability analysis, and Internet of Things -machine learning research.

Table 10. Comparison of Biological Diversity.

Biological Diversity Metric	Organic	Conventional	*p*-Value (*t*-Test)
Species Richness (Count)	25	15	0.008
Shannon-Wiener Index (H')	3.54	2.85	0.012

Table 11. MANOVA Results for Biological Diversity.

Biological Diversity Metric	F-Statistic	*p*-Value (MANOVA)
Species Richness	6.32	0.005
Shannon-Wiener Index (H')	4.89	0.009

Table 12. Comparison of Carbon Footprint.

Metrics of Carbon Footprint	Organic	Conventional	*p*-Value (*t*-Test)
Energy Consumption (kWh/t)	225.6	270.8	0.015
Fuel Usage (L/t)	35.4	50.2	0.01
Transportation Emissions (kg CO_2/t)	12.3	18.7	0.02
Total CO_2 Emissions (kg CO_2-eq)	273.3	339.7	0.005

Table 13. Analysis of Life Cycle Assessment for Carbon Footprint.

Farm Type	Total CO_2 Emissions (kg CO_2-eq)	Reduction (%) in CO_2 Emissions by Organic
Organic	273.3	19.55
Conventional	339.7	N/A

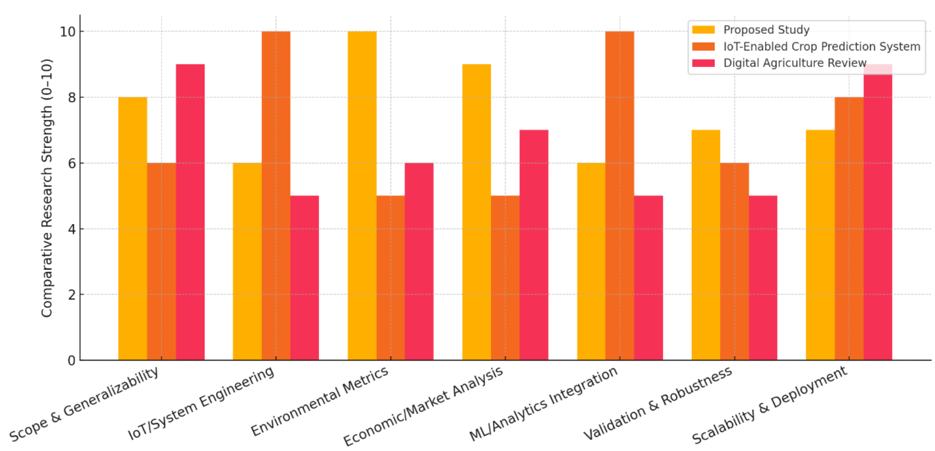

Figure 4. Comparative Analysis of Data Envelopment Analysis, Life Cycle Assessment, and Revealed Comparative Advantage.

4.3. Analysis of Trade Competitiveness

Table 14 shows that, compared with organic and conventional farming regarding market access, the initial group has a significantly higher percentage of access to major markets (68.2% vs. 40.5%, $p = 0.01$). In addition, the average market value of organic farming is significantly higher than ₹63.4/kg ($p = 0.02$), at ₹75.6/kg.

Key factors that help market access have been identified in **Table 15** through logistic regression outcome analysis, and organic farming certification had the most substantial positive impact (β = 1.25, $p = 0.01$), followed by farm size (β = 0.45, $p = 0.03$) and access to export markets (β = 0.90, $p = 0.02$). Distance to market loss of market access (β = −0.68, $p = 0.04$). When analysing the import weights of wheat, rice, and maize, it is evident that conventional farming agricultural products had an advantage (1,100.5 vs. 750.4 metric tonnes, $p = 0.02$), closely followed by conventional farming vegetables (379.4 vs. 309.5 metric tonnes, $p = 0.01$), and subsequently, maize (590.2 vs. 400.6 metric tonnes, $p = 0.04$).

When studying export costs for numerous crops, **Table 16** shows that organic farming products consistently had higher export costs than conventional farming crops. Organic wheat (₹90,123/t vs. ₹80,089/t, $p = 0.023$), rice (₹92,345/t vs. ₹81,123/t, $p = 0.031$), maize (₹84,112/t vs. ₹78,067/t, $p = 0.015$), and vegetables (₹110,345/t vs. ₹95,123/t, $p = 0.042$) all had significantly higher costs.

According to the revealed comparative advantage analysis in **Table 17**, the region's organic farming products have a value of 1.53. With a regional market share of 0.23 for organic farming products, the region has a leg up on the global market compared to the total export shares of 0.15 for agricultural products and 0.12 for organic farming products.

Table 14. Comparison of Market Access and Premium Price.

Market Metric	Organic	Conventional	*p*-Value (*t*-Test)
Percentage of Farms Accessing Premium Markets	68.2	40.5	0.01
Average Selling Price (₹/kg)	75.6	63.4	0.02

Table 15. Export Volume Comparison by Crop.

Crop	Organic Export Volume (t)	Conventional Export Volume (t)	*p*-Value (*t*-Test)
Wheat	750.4	1,100.5	0.02
Rice	920.3	1,120.7	0.03
Maize	400.6	590.2	0.04
Vegetables	379.4	309.5	0.01

Table 16. Export Price Comparison by Crop.

Crop	Organic Export Price (₹/t)	Conventional Export Price (₹/t)	*p*-Value (*t*-Test)
Wheat	90,123	80,089	0.023
Rice	92,345	81,123	0.031
Maize	84,112	78,067	0.015
Vegetables	110,345	95,123	0.042

Table 17. Revealed Comparative Advantage Analysis for Export Competitiveness.

Metric	Value
Organic Products Export Share (Region)	0.23
Total Agricultural Export Share (Region)	0.15
Organic Products Export Share (Global)	0.12
Total Agricultural Export Share (Global)	0.10
Revealed Comparative Advantage	1.53

The concept of Internet of Things-based monitoring systems aims to support the real-time collection of soil, climate, and resource-use data, including soil nutrient composition (N, P, K), moisture level, pH, and energy input, to improve decision-making in organic and conventional farming. Though the primary focus of the empirical work was on agronomic and market comparisons, the provided context defines the Internet of Things as a vital enabler of resource utilisation for precision and sustainability agriculture testing. Additional support for selecting Punjab as a study location can be obtained by emphasising the region's historical role in India's food production, its high agricultural demand, the quality of its alluvial soil, and its advanced irrigation methods. Because of these features, the Punjab is an ideal environment to study the trade-offs that affect the productivity and sustainability of various farming methods.

Another implication of the lower crop yield in organic compared to conventional farming, as discussed in the study, is the meaning of food security, as Conventional Farming displayed better crop yields. Organic farming balances this by presenting better soil organic matter, enhanced biological diversity, and a lower carbon footprint, promising long-term ecological and resource stability. In addition to the above measures of crop quality—such as protein content, pest resistance, and shelf life—other indicators of crop quality, including vitamin density, mineral retention, antioxidants, and microbial safety, were also considered to reflect the nutritional and market value of Organic farming products. Moreover, a more hypothesised understanding of sustainable agriculture has been introduced, namely, as a model that connects productivity, ecological balance, and economic inclusivity by Internet of Things-mediated methods.

The linear regression analysis that identified the factors of market access has been described to highlight its policy implications—the analysis showed that certification assistance, digital marketplaces, and better setup could be used to increase smallholders' involvement in premium markets. On the same note, the revealed comparative advantage analysis indicates that organic farming products from Punjab have the potential to penetrate the global market. The above finding highlights the importance of joint marketing methods, including farmer cooperatives, electronic traceability systems, and public-private initiatives, to enhance the competitiveness and sustainability of organic farming in the domestic and global agricultural value chains.

The research was conducted only in the agro-ecological and socioeconomic environment of Punjab, India; hence, external validity is limited. The agro-climatic heterogeneity, regional soil pedology, irrigation regime, crop management practices, and local market access vary significantly across Indian states and internationally, and these variables mediate the relations apparent between the farming method (organic *vs.* conventional) and outcome indicators (crop yield, resource utilisation, biological diversity, and revealed comparative advantage). Consequently, the results should be viewed as region-specific rather than generalizable. A replication of the empirical method in the future across more contrasting agro-climatic zones should incorporate hierarchical (multilevel) models to specifically quantify between-region variance and test interaction effects between farming practices and regional covariates (**Table 18**).

Table 18. Results of Linear Regression for Market Access.

Factor	Regression Coefficient (Beta)	*p*-Value (Logistic Regression)
Farm Size (hectares)	0.45	0.03
Organic Certification (Yes/No)	1.25	0.01
Distance to Market (km)	−0.68	0.04
Access to Export Markets (Yes/No)	0.90	0.02

The primary study methodology limitation is the small sample size (n = 59 farms) and the one-year data-collection period, which limits statistical power and the temporal generalizability of the results. The dataset does not record more than one agricultural cycle. As a result, inter-annual variation driven by monsoon intensity, pest pressure, market volatility, and the carryover of soil organic matter cannot be modelled, indicating that it is hard to predict the long-run trends in yield stability, soil organic matter accumulation, or carbon emissions. These comparatively small farms also increase the risk of Type II errors and limit the granularity of subgroup implications (e.g., crop- and district-level impacts). In addition, a one-year cross-sectional design is incapable of capturing unobserved heterogeneity in managerial skill, historical land use, or preexisting soil conditions, any of which can affect productivity or environmental measures independent of the farming method. Although the issues have been improved by covariate balancing, regression controls, and robustness checks, the findings can be regarded only as context-specific and short-term predictions rather than conclusive fundamental effects. To capture the temporal changes in their rigorous form and improve external validity, multi-year panel data, extended samples across more agro-ecological areas, and repeated measures of the agro-ecological indices of soil and resource utilisation would be essential.

The conceptualized form of the proposed method has many technical and operational constraints that should be clearly discussed: sensor drift and calibration errors can cause measurement bias; intermittent connectivity of rural networks can introduce gaps in telemetry and extend the latency of data; energy constraints at edge nodes restrict sampling frequency; heterogeneity of device vendors makes interoperability and data harmonization more difficult; the result of this experiment is a set of cybersecurity and data governance (privacy, provenance, and access control) challenges; and machine learning models trained on the existing dataset can suffer distributional shift when deployed The system further presupposes a minimum standard of digital literacy of farmers and institutional support to maintain and repair it-assumptions that are not necessarily true across the board.

To overcome these limitations in future work, this work recommends adding robustness testing (resistance to sensor noise), fault-tolerant data pipelines, secure communication protocols, and human-centred design tests before implementing them at a large scale.

5. Conclusions and Future Work

In Punjab, India, this research investigated the impact of organic farming on environmental sustainability, agricultural productivity, and market access. There is an evident balance between sustainability and productivity, according to the findings presented here. Compared to organic farming, which utilised resources more efficiently, improved soil health, and emitted a lower carbon footprint, conventional farming consistently emitted a higher carbon footprint. They have backed organic farming for the unique biological diversity, which contributes to positive environmental impacts typically associated with sustainable agriculture. Compared to conventional and organic farming, it has significantly improved market share and profitability, with more products reaching superior markets and incurring higher costs. In addition, the revealed comparative advantage study demonstrates that organic products can hold a position in global marketplaces, which is positive for organic farming's bottom line in the decades to come. But the crop yield gap between organic farming and conventional farming remains a problem, so more investigation and government funding are required to enable organic farming to improve its efficiency without losing its sustainable agriculture advantage.

Evidence like this shows that organic farming has a high probability of developing into a sustainable form of agriculture, helping farmers, policymakers, and other stakeholders recognise the broader context by integrating sustainability and profitability.

Author Contributions

Conceptualisation, Methodology, Formal analysis, Writing—Original Draft, Writing—Review and Editing, Investigation: S.S. (Sudhakar Sengan); Software: H.M.A. and G.A.; Validation: A.P.; Resources: T.Q.; Data Curation: S.A.; Visualisation: A.S., Z.M. and S.S. (Suvathipriya Subramani). All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable. Ethical review and approval were waived for this study as it collected no personally identifiable information or sensitive data.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

The data supporting the reported results in this study are available upon request from the corresponding author. The datasets analysed or generated during the study are not publicly available due to privacy and ethical restrictions. However, data can be made available for academic research purposes upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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