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ENVIRONMENTAL AND ECONOMIC IMPACTS OF CARBON EMISSIONS IN POTATO AND MAIZE PRODUCTION SYSTEMS: EVIDENCE FROM PUNJAB, PAKISTAN

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ABSTRACT

Climate change affects agriculture adversely, and at the same time, agriculture is a major contributor to greenhouse gas emissions. In the District Okara of Pakistan, an important potato and maize-producing area, it stands 4th in potato and 3rd in maize production in the country. Increased CO2 levels cause an imbalance in greenhouse gases, which adversely affects crop cycles and increases pests. Climate-related pest pressure has resulted in crop losses of 28-45%. This study aims to estimate the carbon footprint of potato and maize production, analyze their profitability and terms of trade, and identify the key factors influencing carbon emissions and farm profitability. Primary data were collected from a sample of 240 respondents, comprising 120 potato producers and 120 maize producers from District Okara. Profitability was assessed using a net benefit approach, calculated as total revenue minus production costs, while terms of trade were estimated as the ratio of output value to input costs. Ordinary Least Squares (OLS) regression analysis was employed to estimate carbon emissions associated with major production inputs. The results indicate that the average carbon footprint for large, medium, and small farmers was 7.50 m^3, 6.90 m^3, and 6.24 m^3, respectively. Fertilizers, pesticides, diesel, and electricity were identified as the major sources of carbon emissions, contributing approximately 613.22 kg CO_2-equivalent per annum. Water footprint analysis revealed substantial variation among farm sizes, with large, medium, and small farmers recording water footprints of 1460.23 mm, 69.2 mm, and 2807.1 mm, respectively. Despite a high dependence on external and off-season inputs, potato and maize production remained economically viable, with an average market price of approximately PKR 2,800* per mound. These results emphasize the importance of efficient use of inputs and emissions reduction to enhance the sustainability of agricultural systems in Pakistan.

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INTRODUCTION

The agricultural sector is one of the most vulnerable sectors to climate change. On the other hand, it contributes towards greenhouse gas emissions, which are the prime factor of climate change (Xing and Wang, 2024; Omotoso and Omotayo, 2024; Sokal and Kachel, 2025). In modern times, the serious threat is climate change, which has a significant impact of socio-economic factors like energy usage, health assessment management, and food fabrication (Vermeulen et al., 2012). Climate change is a serious threat in modern times and has significant results for socio economics sector, such as food fabrication, energy usage, health, and natural assets management (Eckstein et al., 2021). Nowadays, the world is facing about 500-600 annually usual disaster (Ali et al., 2017). The availability of freshwater is another major problem, which is due to climate change. Developed countries account for a substantial share of historical greenhouse gas emissions, while developing countries experience a disproportionate burden of climate change impacts (Omotoso and Omotayo, 2024). Despite contributing a relatively small share to global CO_2 emissions, Pakistan is consistently ranked among the most climate-vulnerable countries worldwide (Eckstein et al., 2021). According to recent Global Climate Risk Index and IPCC assessments, Pakistan frequently appears among the top ten countries most affected by climate-related extreme events, including floods, heat waves, and water stress, reflecting its high exposure and limited adaptive capacity (Ali et al., 2017). The agricultural sector remains an essential part of the Pakistan economy, as it makes a significant contribution to the country's output. During FY 2024-25, the agricultural sector contributed 23.5 % to the Gross Domestic Product (GDP) of Pakistan. Meanwhile, the agricultural sector showed a moderate growth of 0.56 % in the given financial year. The livestock segment was the major contributor to this growth, recording an impressive 4.72 % increase. The agricultural sector remains one of the largest employers of people in the country. It manages to employ over a third of the country's workforce. This is particularly observed in the rural areas where the agricultural sector helps the community achieve food security.

Maize is one of the key cereal crops in Pakistan and is the third major crop based on its use for both food and livestock feeds. In FY 2024–25, maize was estimated to have been grown on 1.44 million hectares of land with a production level of 8.24 million tonnes despite the area and production declining compared to the previous year. Though the data available indicates some variation in the production level of the crop in the country, Punjab Province remains the major maize-producing region based on its favorable agro-climatic conditions and the agricultural infrastructure that supports irrigation. This production level still indicates the continued relevance of the crop in providing livestock feeds in the agriculture-related economy of Pakistan (Government of Pakistan, 2025).

Potato (*S. tuberosum L.)* is one of the most valuable food and nutritious crop species in the world and has always been one of the top four food crops in overall production (Hameed et al., 2024). Potatoes require well-drained and slightly fertile soil and can be grown within a moderate climatic zone where temperature fluctuations are between 16°C and 24°C. The average production of potatoes in developing countries has increased and is now ranging between 15 and 30 t/ha (Hu et al., 2025). In the context of Pakistan, not only has the area and production of potatoes increased, but more than 0.75 million hectares are under their cultivation, with the country producing over 6 million tons each year, with the major proportion being used by the Punjab region owing to its irrigable and manageable circumstances (Government of Pakistan, 2025).

Agriculture is a notable source of GHG emissions, emitting about 14% of total GHG emissions through N_2O emissions during soil operations and use of fertilizers; CH4 emissions during enteric fermentation and rice cultivation; and CO2 emissions during mechanization and use of land. The share of agriculture in GHG emissions is significant due to both direct emission sources like enteric fermentation in livestock, soil activities, crop residue decay, and fossil fuel consumption; and indirect emission sources like loss of N during application of organic or chemical fertilizers and changes in land use outside croplands. Emission mitigation in agriculture will come through optimized nitrogen use to reduce N_2O emissions, conservation tillage and cover cropping that enhance soil carbon storage, and the policy level, such as policies that limit deforestation and conversion of forests into agricultural land (Canton, 2021; Wardhana and Prawira, 2024).

Carbon Footprint and Climate Change Context

"Carbon footprint" is regarded as a sum of direct and indirect GHG emissions in the form of CO_2 produced through human activities or consumption patterns. As a result of increasing scientific understanding of the negative consequences of high CO_2 levels for human health, the environment, and agricultural productivity, "climate change" is currently regarded as "one of the most significant global challenges" (Lee et al., 2023). The term “footprint” was originally formulated by Wackernagel and Rees (1996) with regard to the effects of consumption and production activities on the environment. As opposed to general GHG calculations, carbon footprint assessment does take into account processes, activities, and life cycle stages related to consumption and production (Wiedmann and Minx, 2008). Certain researchers have proposed that the effects related to carbon could be quantified in terms of land use, giving rise to the broader term “climate footprint” (Morera et al., 2016).

Emissions of carbon became an international concern with the emergence of a number of assessment reports by the Intergovernmental Panel on Climate Change, which highlighted the importance of having a balanced accounting of the supply chain and land use changes associated with the energy and agricultural sectors (Calvin et al., 2023). For example, despite the fact that any form of emissions associated with agricultural activities and energy consumption would attract considerable attention, the concern for supply chain and land use changes associated with such emissions would still be low, despite the substantial contribution they make, though less. Since the year 1970, the world has seen a doubling of the growth in food consumption and a rapid increase in population, such that now, the sector of agriculture, forestry, and land use change contributes almost a quarter of global GHG emissions (Smith et al., 2014; Daubenfeld et al., 2025). The GHGs produced in the sector primarily come from the release of methane gas (CH4) from livestock, nitrous oxide (N2O) from fertilizer, and carbon losses from land use change.

Climate change has already exacerbated environmental stresses such as irregular monsoon seasons, temperature fluctuations, glacio-retraction, floods, and droughts and sea-level rise, with serious impacts on food and water security (Wardhana and Prawira, 2024; Bilgili and Tokmakci 2025). Pakistan, in spite of having less globalGHG emission, ranks among the countries that are highly exposed to climate change due to its geographic, social, and economic conditions.

Potato Production and Environmental Challenges

Potato is a nutritionally valuable crop, the fourth most valuable crop worldwide after maize, wheat, and rice (Mishra et al., 2024). Potatoes can be cultivated on well-drained soil with low saline content. Moderate temperatures between 16° and 24° are preferred for the crop. Potatoes are still often grown on low-yielding fields due to a lack of access to high-quality inputs and technologies on a wide scale, especially in developing nations. Global potato production is above 370 million tons a year, being a staple food for more than three billion people (Daubenfeld et al., 2025).

Potato production in Pakistan has greatly increased since the independence era, when it gained economic value for both producers and consumers. The major contributor to agricultural income is the production of potatoes, as it is considered a commodity with a high production potential. About 95% of the production is from the province of Punjab (Government of Pakistan, 2025). However, input costs, pests, and post-production losses remain a problem for the sector, aside from the issue of pesticide overuse, especially in the production of potatoes.

Maize Production and Resource Constraints

Corn is among the most frequently grown crops worldwide and an essential component of the agricultural sector in the economy of Pakistan, both for food, feed, and industrial purposes. The maize-growing areas in the country are limited to Punjab and Khyber Pakhtunkhwa provinces, which alone contribute to the overall maize production in the country (Hussain et al., 2023). The use of hybrid crops has greatly boosted maize productivity, yet the actual productivity level isn’t optimal, owing to water deficiency, pests, improper use of fertilizers, and unavailability of advanced inputs.

Maize production is highly associated with water availability, as about two-thirds of the crop depends on irrigation. Climate-induced water scarcity has already resulted in reduced yields under rain-fed and marginal conditions. Efficient management of water and nutrients, therefore, remains imperative in the light of Flammini et al. (2021). Improved tillage, integrated weed management, and balanced fertilizer use improve productivity while reducing environmental impacts.

Water Scarcity and Sustainability in Pakistan

Water scarcity presents an alarming challenge to agricultural sustainability in Pakistan. About 70% of the country’s existing water resources are under varying levels of stress, largely attributed to groundwater extraction, contamination, and climate change (Ishaque et al., 2023). Alarmingly, accounts by both domestic and global bodies indicate that the country has already entered an era of water scarcity, with the rate at which each population member has access to each cubic meter of water decreasing at an alarming rate (Begum and Ali, 2025).

The aim of this study is the estimation of water and carbon footprint in potato and maize cultivated areas .so at the National level, for the efficient use of water and agricultural resources, policies and recommendations should be suggested. Due to the main potato and maize growing area in District Okara, the main aim is to find out those gases that are heavily involved in the production of the potato crop and released at the highest level, and policy suggestions for the reduction of carbon emissions can be made.

MATERIALS AND METHODS

Scientific explanation of methodology: It is very necessary to have a suitable methodology for the successful completion of any research study. All the steps, from data gathering to policy recommendation, comprise the methodology. It also comprises techniques of collecting data from valid sources, selection of variables, and application of appropriate analytical techniques and correct model specification to find the results.

It shows that the major purposes of research are to explain the many tools to researchers. Since there are various approaches for different study designs and inquiries into questions, in sample relationships, quantitative research is able to find out many farmers who want to choose between qualitative and quantitative techniques; the majority of the researchers chose qualitative data.

Sampling technique (strata)

The work was conducted in District Okara (Figure 1), a large potato and maize-producing region of Punjab Province, Pakistan. Thus, Region Okara will be selected as the study area for this study because of this reason, this region is exceptionally specific for potato and maize production. Three tehsils of the district Okara named, Okara, Depalpur, and Renala Khurd, would be selected for the survey. Then, four villages for each tehsil would be selected randomly, and then 10 potato production farmers for each village would also be selected, randomly, and 120 farmers would be collected. Potato and maize production are dependent upon the timely presence of water. To calculate the data, various input factors for analysis and calculation for the farmers, mixed methodologies were employed. In the categories of large, medium, and small farmers, the carbon footprint was calculated.

Study Area

District Okara is considered one of the prominent agricultural areas of Pakistan, specifically recognized as a potato yielder; hence, this region was chosen as the study area. The district has three tehsils: Okara, Depalpur, and Renala Khurd. Along with rich agricultural land, the region has three military farms, a livestock farm, and a sugar mill established by the government, which plays a significant part in the development of the agricultural field. During the past few years, the number of rice mills has increased in this region, too.

District Okara geographically shares boundaries with District Kasur and Sahiwal in the east, Pakpattan in the west, and Bahawalnagar, Faisalabad, and Nankana Sahib in the south.

For the purpose of data acquisition, a multistage random sampling method was used. The initial stage involved the random selection of Tehsil Okara. The next stage entailed the random selection of villages from the chosen tehsil. Lastly, fifteen potato as well as maize growers were selected using a random sampling method from every village, giving a sample population of 120 farmers.

Data was also gathered both qualitatively and quantitatively from farmers to estimate carbon footprint, water footprint, and probabilistic effects. The farmers were classified into three groups based on landhold size. These include small farmers who own land between 1 and 5 acres, medium farmers who farm approximately 5.1 acres of land, and large farmers who use over 12.5 acres of land for crop production.

Figure 1. Map of District Okara.

Table 1. Distribution of sample farmers by farm size category.

Farmer Category	Potato Farmers (Frequency)	Potato Farmers (%)	Maize Farmers (Frequency)	Maize Farmers (%)
Small Farmers (< 5 acres)	60	50.00	70	41.00
Medium Farmers (5–<12.5 acres)	35	29.16	30	39.00
Large Farmers (≥12.5 acres)	25	20.83	20	21.00
Total	120	100	120	100

The distribution of potato and MAIZE farmers based on farm sizes is shown in Table 1. The findings show that small farmers make up the greatest proportion of both potato and MAIZE farmers. The table shows that small farmers make up 50% of potato producers and 41% of MAIZE producers. Medium farmers make up 29.16% of potato farmers and 39% of MAIZE farmers. The largest farmers make up the smallest proportion of each of the two types of farmers. Generally, based on the distribution of farmers by farm sizes shown in Table 1 above, it is evident that there exists a rather small to medium-sized farm structure.

Interview Schedule

The interview method has been adopted as the chief instrument of data acquisition. The structured interview schedule was devised in English; however, to ensure greater understanding of the questions with an aim to acquire maximal and accurate data, it had to be asked in Punjabi and Urdu in keeping with the local setting of the farmers. Careful translation had to be done in order to preserve the original meaning of the questions. "The interview schedule had a number of advantages, including:"

Conducting interviews allows the researcher to have more control over the data collection process, which enables them to direct the interview and make sure that the right areas are discussed. Additionally, conducting interviews makes it easier to obtain more information, as the respondents are able to elaborate on their experiences, which might not be possible when conducting structured interviews. Moreover, conducting interviews helps to increase the accuracy of the information obtained, as the researcher is able to clarify any ambiguities.

Problems faced by investigators

During the process of data collection, some challenges were encountered. Some of the participants in the sample population were illiterate and did not understand the significance of social research. This made it necessary to spend extra time and effort to convince them of the purpose and significance of the research. Some of the participants were afraid that the data they provided could be used against them. This made them reluctant to provide the correct data. Some of the participants refused to be interviewed by the research team. Some farmers provided false information, especially when it came to sensitive issues like the size of their families and their average monthly income. They also showed non-cooperative behavior during the process of data collection.

Data Analysis

The quantitative data collected were analyzed using descriptive and univariate analysis, among other statistical techniques. Descriptive statistics were employed in summarizing data through the use of percentages and frequency distributions to clearly understand the characteristics of both dependent and independent variables. Data processing and analysis were done using the Statistical Package for Social Sciences. SPSS is widely recognized for its efficiency, accuracy, and handling of complicated datasets and is, therefore, a reliable tool in quantitative research. It supports rapid data entry, storage for a longer period, and systematic analyses, hence informing appropriate decisions by researchers.

Before undergoing analysis, the data were coded in an appropriate manner to allow for automated analysis. In conducting univariate analysis, frequency distribution was adopted in this study as the first step to determine distribution patterns of variables in relation to dependent and independent factors.

Percentage

In the present day, to compare the data, many kinds of percentages are used. By using the following formula percentage were defined as.

$$\text{Percentage} = \frac{F}{N} \times 100 \qquad (1)$$

Where,

P=%

F=Frequency

N=total no of Mean frequency

The indication of the observed and magnitude value was given by the mean. A bar over a symbol of a variable that is represented.

Estimation of Carbon Footprints

The coefficients employed by the researcher in calculating the level of production of the greenhouse gas produced by different input measures in maize and potato crop production are indicated. The GHG emission coefficients employed in the estimation of the carbon footprint due to agricultural inputs in the production of potato and maize. These coefficients are the measures used to quantify the level of greenhouse gas in kilograms of carbon dioxide equivalent produced by the different agricultural inputs in the production of potatoes and maize, converted using the coefficients.

Factors such as energy inputs in terms of diesel oil consumption and electricity consumption are indicated to have relatively high emission factors because of their connection to fossil fuel burning and electric power production. The emission factor associated with diesel oil consumption is 2.76 kg CO_2 equivalents per liter, while electricity consumption has a factor of 0.489 kg CO_2 equivalents per kWh (Dyer & Desjardins, 2006; Garcia et al., 2011). Of the chemical fertilizers, Nitrogen (N) has the largest emission coefficient of 1.3 kg CO2-eq per kg of substance emitted, suggesting its significant impact on greenhouse gas emissions from agricultural activities because of its high energy consumption during production. However, Phosphorus (P2O5) and Potassium (K2O) fertilizers have lower emission coefficients at 0.2 kg CO2-eq per kg of substance emitted (Lal, 2004).

Pesticide use is characterized by a material with high emission intensity, with a value of 6.3 kg CO_2-eq per kg and 5.1 kg CO_2-eq per kg for herbicides and insecticides, respectively, reflecting their importance in carbon emissions (Lal, 2004).

In general, the emission coefficients, anchored in literature reviews of widely cited studies, bring forward a standardized scheme to derive input-specific and total carbon emissions in this study. The emission coefficients make it possible to compare contributions of various farm inputs to GHG emissions regardless of farm sizes.

Estimation of Water Use Efficiency

Water footprint measurement can be done by first measuring water use efficiency (WUE), that is, how efficiently water is used for irrigation. To calculate the water use efficiency, we find the total irrigated water, which is the total sum of canal water and tube well water; it is then converted into inches by multiplying by the water depth in the field, which is taken as 3 inches standard. The total volume of water is then converted into milliliters. Now, to calculate the water use efficiency, the required water was divided by the total volume of water found by the above steps. It must be noted that the required water for the cotton crop is 1100 millimeters, which was taken as standard.

$$\text{Water use Efficeincy} = \frac{Required\ water(mm)}{Total\ irrgated\ water(mm)} \quad (2)$$

Estimation of Water Footprints

To calculate the water footprint, first, the yield (kg/ha) is to be calculated, then total water usage is calculated in cubic meters by converting total water irrigated in meters. Then, the total irrigated water in meters is to be multiplied by the total area. The last step is to calculate the yield / total irrigated water of one acre. The formula is given below:

$$\text{Water Footprints} = \frac{Yield\ in\ KG\ (per\ acre)}{voulme\ of\ irrigated\ area\ (m^3)} \quad (3)$$

Identification of the Impact of Carbon Footprint and Profitability

We used the ordinary Least Squares (OLS) estimator to find the relationship between the dependent variable and one or more ordinal, ratio, nominal, and interval independent variables. The total carbon emission was selected as the dependent variable and socio-economic factors like family size(number), age(years), farmer types, commercial and specialized bank, and farming experiencing consider as the independent variables.

The general regression equation is as follows:

Total carbon emission =F (Education, Family Size, Experience, Area)

$$\text{Total carbon emission} = B0 + B1X1 + B2X2 + \cdots + BIXI + e \quad (4)$$

Where,

B_0=Constant

B_i=coefficient

X_i= Independent variable

The Mean Comparison by Test

Mean comparison t-test is done by compare mean between two variables.

RESULT AND DISCUSSION

Scientific reasoning, data collection, data interpretation, and data analysis are the basic fundamentals in the construction of the logical building. If we miss or avoid these parameters, we cannot derive and predict the achievement of a reliable conclusion in scientific research. Parameters of many kinds are arranged before data collection, and the information that the conclusion provides is used to draw the findings.

Cost of Production

The data revealed that the scale of farming impacts the cost of preparing the land, which stood at an average of PKR 3,345 for small, PKR 2,478 for medium, and PKR 3,149 for large farmers. The analysis also revealed that small farmers had relatively higher production costs, whereas medium and large farmers had relatively low production unit costs.

The result shows that there are variations in the gross income, net income, and average costs of production for different categories of farmers. Small farmers obtained a gross income of PKR 71,400 with a net profit of PKR 10,119, along with relatively higher costs per acre, while large farmers obtained higher profits through increased availability of land, investment, irrigation, and labor, which helped them in adopting efficient methods of production. Medium farmers produced the highest yield per acre, followed by large farmers, while small farmers produced a comparatively lower yield.

A detailed analysis of the production costs per acre for each category of farm sizes, which include small, medium, and large farmers, as well as the average for the entire sample, is shown in Table 2.

The analysis indicates that the costs involved for land preparation are significantly higher for both small and large farmers compared to medium-scale farmers, due to variations in the utilization and operation of machinery. The seed costs, which involve seed rate, treatment, and the process of seed sowing, are relatively uniform across the various levels of farm sizes, but slightly higher for the large-scale farmers.

Irrigation costs account for a sizeable proportion of total production costs, especially for the small and medium categories of farmers, reflecting their greater dependence on tube well irrigation. Intercultural operations and labor-related activities account for another major cost component, comprising thinning, inter-culture with tractors, and watercourse cleaning, whose expenses are observed to rise with farm size, reflecting higher intensity of labor and mechanization on larger farms.

The cost of weedicides, farmyard manure, and fertilizers is significantly higher for medium and large farmers. The cost of fertilizers is one of the major components. The fixed costs, such as land rent, mark-up, abiana, and pickers' cost, have also been found significant. The average cost of production per acre is significantly higher for small farmers, followed by medium and large farmers.

The yield rates are relatively high for medium farmers, followed by large farmers; small farmers have the least yield. The profitability ratio indicates that large farmers have the highest benefit-cost ratio of 1.50 compared to medium and small farmers, who have 1.43 and 1.22 BCR, respectively. The following results indicate the existence of economies of scale and the cost and productivity problems associated with small-scale farming.

Benefit–Cost Ratio (BCR) Analysis

Results after using the analytical approach showed that there was indeed a significant difference in the cost structure of conventional potato and maize production, including expenses related to fertilizers, organic inputs, land preparation, pesticides, irrigation charges, marketing, labor, transportation, and other input costs. These cost components vary among farm sizes since input use intensity and resource accessibility differ.

Table 2. Cost of production.

Activity	Small Farmers (n = 90)			Medium Farmers (n= 80)			Large Farmers (n = 70)			Total sample (n = 240)		
	Unit	Nos	Amount	Unit	Nos	Amount	Unit	Nos	Amount	Unit	Nos	Amount
Land preparation												
Planter	No's	2	115	Nos	2	660	No's	1	490	No's	1	599
Rotavator	No's	2	790	Nos	1	720	No's	1.03	660	No's	1	650
Ploughing	No's	2	1560	Nos	3	100	No's	3.65	1000	No's	3	1227
Laser land leveling	No's	2	880	Nos	1	998	No's	1.01	999	No's	0.9	1000
Subtotal			3345			2478			3149			3476
Seed												
Seed rate + drilling cost	Kg	5.74	1235	Kg	4.11	1720	Kg	4.89	1800	Kg	4.11	1016
Seed treatment		0	500			30			30			30
Drilling + Ridge Sowing		0.60	497		0.17	554		0.10	590		0.14	554
Manual labor		0.10	90		0.13	80		0.35	85		0.12	80
Subtotal		0	2322			2384			2505			1680
Irrigation												
Canal water/Abiana			85			85			85			85
Tube well Water	Hrs.	2	2430	Hrs.	2	2200	Hrs.	2	1700	Hrs.	2	2100
Mixed (tube well + canal)		1	330		1	290		1	290		1	380
Subtotal			2845			2575			2075			2565
Manual Thinning		5	1400		5	1700		5	2000		5	1500
Inter culture with tractor		2	1700		2	1900		2	2100		2	2000
Water course cleaning		5	1700		5	1550		5	157		5	15000
Subtotal			4800			5150			5670			18500
Weedicide spray	Nos		4100	No's		4590	No's		4350	No's		3250
Farmyard manure + transport	Nos	0.20	300	No's	0.31	400	No's	0.20	300	No's	0.31	333
Subtotal			4400			4990			4650			3583
Fertilizer												
DAP	Bags	1.5	3100	Bags	1.5	3000	Bags	1.5	3203	Bags	1.29	3478
Urea	Bags	2.5	1921	Bags	2.5	3203	Bags	2.5	4000	Bags	2.55	3566
Potash	Bags	1.5	2500	Bags	2	3100	Bags	1	2200	Bags	0.62	3000
Subtotal			7521			9303			9403			10044
Markup @ 12%			1660			1660			1660			1740
Land rent			15000			15000			15000			19000
Abiana			70			70			70			90
Payment to pickers			6920			7612			8212			8612
Average cost			58373			51650			51105			59436
Yield per acre			18.99			22.70			21.00			21.73
Market price			2800*			2800*			2800*			3100*
Gross income			71400			73900			7700			67373
Net gains/Net profit			10119			10261			7742			7937
Benefit Cost Ratio (BCR)			1.22			1.430			1.50			1.13

(*) The star shows that the market price, which is issue b government.

The test results show that there are significant differences between gross income, net income, and average production costs among small, medium, and large farmers. Small farmers incurred relatively higher production costs and lower profitability, whereas medium and large farmers reported better financial performances. The net returns of larger farmers were greater, especially because of greater access to land resources, capital, labor, and farm machinery, which ensured efficient production methods.

The Benefit–Cost Ratio (BCR) was calculated using the standard formula:

BCR = Total Revenue ÷ Total Cost (5)

These results indicate that potato and maize cultivation are economically feasible in District Okara, as the calculated BCR values are greater than unity for all categories of farms. An overall BCR value of around 1.3 depicts that an investment of PKR 1 generates a return of about PKR 1.30, which justifies the fact that the cultivation of these crops is profitable in the area under study. Furthermore, it is evident from the increasing BCR values that bigger farm size exerts economies of scale in production.

A comparison of the benefit-cost ratio (BCR) obtained from the study with the values obtained from previous studies conducted in foreign nations is given in Table 3. It is observed from the result that although the BCR obtained from the study is low compared to the values for India and the USA, it is comparable with the values for Bangladesh. The high values may be due to the increased usage of modern inputs, adoption of high-level technology, and more favorable market conditions. Additionally, high values have been associated with efficient production systems and high degrees of mechanization. However, data gathered from Pakistan tells a different story, as it shows that BCR values are relatively low, implying that production was marginal or even uneconomic. Based on these observations, it can be theorized that while economic profit can be obtained through potato and maize production in Okara, such profit is not as high as that found in other international literature.

Table 4 shows the carbon footprint (kg CO_2-eq per acre) of potato and maize production in District Okara for different categories of farmers. GHGs emissions were calculated by applying standard conversion factors to various significant agricultural inputs, which included fertilizers (DAP, urea, NPK, nitrophosphate, potash), pesticides and weedicides, diesel, and electricity. Emissions were calculated on the basis of intensity in use and expressed in kg CO_2-equivalent per acre. The findings reveal that the carbon footprint, on average, is quite high at around 476.74 kg CO_2-eq per acre among small farmers, 549.26 kg CO_2-eq per acre among medium farmers, and 479.12 kg CO_2-eq per acre among large farmers. In all farm categories, electricity, diesel, and urea turn out to be the major contributors, with a share of nearly 85% in total GHG emissions.

In the case of small-scale farmers, electricity presents the most significant contribution to emissions, followed by diesel and urea. With regard to fertilizers, urea is the major source of fertilizer-related emissions, presenting the highest proportion of total GHGs against a background of DAP, nitrophosphate, and potash. The same trends can also be found for medium farmers, wherein electricity is given the foremost priority concerning emissions, followed by diesel and urea, thus supporting the major role played by energy-intensive factors in the generation process of carbon emissions. In contrast, urea delineates a prominent source for large farmers pertaining to fertilizers, while electricity and diesel are major contributors concerning other sources.

Comparing the current study with previous studies is indicated in Table 4. The carbon footprint values obtained in the current study are lower than those obtained in Kasur and Iran but similar to those obtained for wheat production in India. The results can be attributed to varying crop production practices. The crop production practices differ based on the consumption levels of electricity and fertilizers, irrigation intensity, and production practices. In general, the results imply that the use of energy (electricity and diesel) and nitrogenous fertilizers, especially urea, are the major contributors to the estimated GHG emissions from the cultivation of potatoes and corn. The observed implications suggest the need for irrigation and fertilizer use Best Management Practices that are appropriate for the region and are aimed at making the farming process environmentally less harmful and "carbon-neutral" for the future.

The carbon footprint values for potato and maize per acre for farmers grouped by size are presented in Table 5.

Based on the Table 5, it can be concluded that total GHG emissions per acre differ by size, indicating that medium farmers have high emissions (549.26 kg CO_2-eq/acre), followed by large farmers (479.12 kg CO_2-eq/acre), while small farmers follow closely with a total emission of 476.74 kg CO_2-eq/acre.

In all agricultural categories, electricity, diesel, and fertilizers have been identified as factors that emit large quantities of GHGs. Electricity is the main contributor to emissions, with a share of 39.34% from small farmers, 27% from medium farmers, and 30% from large farmers, thereby emphasizing the high emission nature of irrigation and electricity use in crop production. Diesel fuel is next to electricity and is especially prominent in medium-scale farming setups.

Among fertilizer materials, urea is a major source by itself of emissions pertaining to fertilizers for any size of farmland, followed by DAP fertilizers and nitrogen fertilizers. Emissions from fertilizers account for 12.5% of total emissions for small farmers, 17% for medium farmers, and 12% for large farmers, signifying relatively higher emission intensity related to nutrient management. Emissions related to weedicides and pesticides account for a relatively lower percentage of total GHG emissions for all categories of farmers.

In general, it has been evident from the results that energy consumption, including electricity and diesel, in combination with nitrous fertilizers, accounts for emissions of more than 80% of total GHG emissions in potato and maize production. This indicates that there is a significant need to adopt water-saving irrigation systems, efficient fertilizer practices, and climate-resilient agricultural practices to make potato/maize production GHG emissions-friendly in the study region.

Table 3. Benefit Cost Ratio (BCR).

Study Area	Total Observation	BCR			
		Small	Medium	Large	Overall
Okara	240	1.2	1.4	1.5	1.3

As compared to previous study in District Okara, Pakistan, BCR is going to decrease.

Table 4. Carbon footprint.

Study Area	Total observation	Crop	Carbon footprint			Over all Kg/acre
			Small	Medium	Large	
Okara	240	Potato and Maize	476.74	549.264	479.12	613.22

Table 5. Carbon footprint for different groups of farmers (per acre).

Input	Small Farmers(n=90)		Medium Farmers(n=80)		Large Farmers(n=70)		Total(n=240)
	GHG emissions (kg CO_{2eq} $acre^{-1}$)	Percentage (%)	GHG emissions (kg CO_{2eq} $acre^{-1}$)	Percentage (%)	GHG emissions (kg CO_{2eq} $acre^{-1}$)	Percentage (%)	GHG emissions (kg CO_{2eq} $acre^{-1}$)
Fertilizer	80.34	12.5%	115.67	17%	110.05	12%	102.02
Urea	59.78	12.75%	63..09	9%	69.12	14%	63.90
DAP	19.01	3.10%	25.104	3%	20.20	8%	21.438
Nitro Phos	1.0.1	1.25%	11.90	1%	7.40	3%	6.77
Potash	0.29	0.06%	1.21	0.5%	0.06	1%	0.52
Guara (NPK)	7.83	2.00%	12.90	1%	1.02	0.5%	7.25
Electricity	185.25	39.34%	183.56	27%	189.1	30%	185.97
Diesel (Fuel)	120.45	30.91%	220.21	25%	60.9.	27%	133.85
Weedicide	5.90	2.90%	7.00	0.5%	5.28	0.5%	6.06
Pesticide	23.9	5.00%	24.29	5.00%	15.99	8%	21.39
Total	476.74	100%	549.264	100%	479.12	100%	613.22

The carbon emissions of potato and maize production per kg of product for different sizes of the farming enterprises are presented in Table 6, in kg CO_2-eq kg^{-1}, along with the share of major input sources. From this result, it can be interpreted that carbon emissions per product are different for different sizes of farming enterprises, where medium farmers generate carbon emissions of 26.05 kg CO_2-eq kg^{-1} per kg, which is higher than that generated by small farmers (23.68 kg CO_2-eq kg^{-1}) but lower than that of large farmers (22.47 kg CO_2-eq kg^{-1}).

Across all farm categories, electricity emerges as the dominant contributor to per-kilogram greenhouse gas (GHG) emissions, accounting for 42% of total emissions for small farmers, 38% for medium farmers, and 45% for large farmers. This highlights the carbon-intensive nature of energy use, particularly for irrigation and other on-farm operations. Diesel fuel represents the second-largest emission source, especially among medium and large farmers, reflecting higher levels of mechanization.

Fertilizer-related emissions contribute a smaller but significant share of total emissions per kilogram. In the category of fertilizers, urea has been the single largest contributor in all sizes of farmland, followed by DAP, and other nitrogen-based fertilizers, whereas emissions from potash and nitrophosphate fertilizers have remained negligible. The contribution of emissions from weedicides/pesticides to GHG emissions has remained negligible.

In general, the evidence highlights that the use of energy (electricity and diesel) and the use of nitrogen-based fertilizers are the key sources of carbon emissions on a unit output basis. The lower levels of carbon emissions per unit, which were recorded among larger farmers, are indicative of better efficiency and economies of scale, while high emissions among medium-scale farmers are indicative of relatively poor efficiency on that scale. These points strongly suggest that the use of efficient irrigation and fuel and nitrogen-based fertilizer use are important for the reduction of carbon emissions from the production of potatoes and maize.

Table 6. Carbon footprint for different groups of farmers (per Kg).

Input	Small Farmers		Medium Farmers		Large Farmers		Total
	GHG emissions (kg CO_{2eq} Kg^{-1})	Percentage (%)	GHG emissions (kg CO_{2eq} Kg^{-1})	Percentage (%)	GHG emissions (kg CO_{2eq} Kg^{-1})	Percentage (%)	GHG emissions (kg CO_{2eq} Kg^{-1})
Fertilizer	0.85	13	2.31	10	2.18	10	11.36
Urea	2.00	10%	2.89	10%	2.16	12%	2.35
DAP	0.31	6%	0.71	5%	0.48	5%	0.5
Nitro Phos	0.06	0%	0.06	3%	0.10	2%	0.013
Potash	0.0015	0%	0.007	0%	0.028	0%	0.012
Guara (NPK)	0.20	2%	0.25	4%	0.024	0%	0.158
Electricity	12.06	42%	8.68	38%	8.52	45%	9.0735
Diesel (Fuel)	3.61	22%	10.01	25%	8.1170	29%	0.173
Weedicide	0.15	2%	0.18	2%	0.19	2%	0.17
Pesticide	0.85	3%	0.86	3%	0.62	5%	0.78
Total	23.68	100%	26.047	100%	22.47	100%	44.74

Water Footprint of Potato and Maize Production

Water footprint of potato and maize production in small, medium, and large farmer categories measured with regard to water productivity in kg per m^3 water and water losses in mm. The results clearly show in Table 7 differences in water-use efficiency among farm sizes.

Water productivity is, therefore, highest for small farmers at 6.21 kg/m^3, followed by medium farmers with 6.90 kg/m^3, and highest for large farmers at 7.50 kg/m^3. This pattern would, thus, seem to reflect that irrigation water is being used most efficiently by large farmers. This could be due to their better command over irrigation infrastructure, improved farm management practices, and efficient input use. The all-sample average water productivity is 6.87 kg/m^3. Water losses among the small farmers, in contrast, are very high at 2807.1 mm against 69.2 mm for medium farmers and 1460.23 mm for large farmers. Apparently, inefficiency in irrigation methods, along with poor watercourse maintenance and meager adoption of water-saving technology, might be the reason for the high rate of water loss among small farmers. Even though large farmers harvest more productivity, the losses of water due to farming are still quite significant, and further efficiency enhancements can always be done.

In summary, evidence shows that water use efficiency increases with farm size, and there are difficulties confronting small-scale farmers. The implications of these findings underscore the need to improve irrigation practices, invest in water-saving techniques, and extend services to farmers in an effort to mitigate water losses in growing potato and maize.

Econometrics Result

Econometrics result reviled that profitability and carbon emission have a relationship with cost factor and socio–economic factors. On the production of carbon, socio-economic factors have a positive and significant influence. Income level and education has significant impact on carbon emission, while the use of electricity and diesel have negative relationship with the environment (Garcia et al., 2016). The relationship between profitability and carbon with its independent factors. The main purpose of this study is to estimate the water footprint and carbon footprint of potato and maize production. Kennedy et al. (2015) found the relationship with missing factors of socio-economic factors.

Table 8 shows the results of regression analysis conducted to test the effects of certain socio-economic factors on carbon emissions during potato and maize production. The independent variables used include experience in farming, educational levels, and family sizes. The analysis was conducted using information from 240 farmers of potato and maize.

The output reveals that farming experience significantly affects carbon emissions negatively. The negative coefficient on experience ($\beta = -5.02$, $p < 0.05$) indicates that an increase in farming experience is accompanied by a decrease in carbon emissions by a margin of approximately -5.02 units, net of other factors. This result says that farmers with high levels of experience are most likely to promote effective farming management, leading to a decrease in carbon emissions.

Likewise, education has a negative and statistically significant effect on carbon emissions ($\beta = -0.003$, $p < 0.05$) when controlling for other factors. The result shows that as education rises, carbon emissions fall. This may be because of increased awareness about efficient use of input, innovative approaches towards agricultural practices, and environmentally responsible behavior.

On the contrary, the result for family size shows a positive relationship with carbon emissions ($\beta = 0.002$), suggesting that with an increase in family size, an increase in carbon emissions is observed. This could relate to labor use, on-farm activities, and energy use in larger families.

The constant term also indicates that when all other variables are set to zero, there is expected to be a certain amount of carbon emissions. Carbon emissions are explained by 0.91% variation based on the R^2 value. Despite this, the results offer an important understanding of human and crop production at households that influence carbon emissions.

The findings from the regression analysis estimating the probability impact of the major cost drivers in the production of potatoes and maize on carbon emissions are presented in Table 9. The findings disclose that land preparation cost has a negative and significant coefficient on carbon emissions ($\beta = -0.07$, $p < 0.05$), indicating that increased spending on land preparation, possibly due to improved mechanization, can reduce carbon emissions. On the same note, the cost of seeds has a negative relationship with carbon emissions ($\beta = -0.17$, $p < 0.05$), suggesting that spending on improved seed can enhance efficiency and reduce carbon emissions per output.

In contrast, irrigation cost is positively and significantly associated with carbon emission, $\beta = 0.089$, $p < 0.05$. This implies that a higher irrigation cost, probably due to a rise in the use of electricity and diesel, results in higher carbon emissions. The harvesting cost presents a positive but insignificant influence on emissions and therefore is considered to have a minor influence on carbon outcomes.

Table 7. Water footprint of Potato and Maize.

Size	Small (n=90)	Medium (n=80)	Large (n=70)	Total (n=240)
Water production –kg per m3	6.21	6.90	7.50	6.87
Water losses (mm)	2807.1	69.2	1460.23	1445.51

Table 8. Determinants of carbon emissions in Potato and Maize production.

Factors	Coefficients	P-value
Experience	-05.02** (0.006)	0.561
Education	-0.003** (0.001)	0.124
Family size	0.002** (0.0001)	0.889
Constants	0.012	0.143
R2	0.91%	

Note: In the brackets, the standard error of the coefficient; *, **, *** showed the level of significance at 10%,5%, and 1%, respectively.

Table 9. On the probability effect of different variables.

Factors	Coefficients	P-value
Land preparation cost	-o. o7** (0.18)	0.551
Seed cost	-0.17** (0.28)	
Irrigation cost	0.089** (0.189)	0.115
Harvesting cost	0.009** (0.102)	0.882
Constants	20988 (2867.7)	0.152
R2	50%	

*, **, *** showed the level of significant at 10%,5% and 1% respectively.

The constant term represents the baseline level of emissions when all explanatory variables are zero. The R^2 value of 50% indicates a good model fit, suggesting that half of the variation in carbon emissions is explained by the included cost variables. Overall, results demonstrate how input-related cost decisions-irrigation, particularly, and investment in seed are important drivers of the carbon footprint of crop production.

Discussion

This study therefore provides empirical evidence of the magnitudes and compositions of carbon footprints associated with potato and maize production systems within District Okara, Punjab, Pakistan. The results add to the emerging literature highlighting agriculture as a priority sector for climate change mitigation policies in developing countries, dominated by input-intensive crop production systems. In line with global assessments, the findings show that crop production activities, especially fertilizer use, irrigation, and energy consumption, remain a significant share of GHG emissions in staple and cash crops.

Carbon footprints of potato crop production stood out as appreciably higher compared to maize. Notably, Okara potato crop production is more intensive in the use of synthetic fertilizer application, irrigation events, and mechanization. All these aspects contribute to higher GHG emissions. These results are consistent with Li et al. (2025), who emphasized that GHG emissions mainly relate to nitrogen-based emissions due to fertilizer usage or energy consumption during crop production. Concerning GHG emission sources specifically attributed to agriculture, Tubiello et al. (2022) emphasized that "pre-production inputs and on-farm activities are now driving a significant share of GHG emissions in agri-food systems, particularly in high-input crop systems."

Fertilizers were identified as a significant contributor to the crops, emphasizing the IPCC Working Group III findings on the climatic significance of inefficient nitrogen use (Naidoo, 2022). The usage of higher levels of fertilizer in the Pakistani context, often because of the lack of extension and awareness about the use of fertilizer, was also pointed out in the findings of Kamal et al. (2022). The lower carbon intensity of the maize field can be attributed to the comparatively less usage of fertilizer and irrigation, making it a suitable option for a climate change scenario.

Emissions associated with irrigation activities also made a substantial contribution to the carbon footprint, especially for potatoes. Aquifer extraction through diesel or electricity-driven tube wells forms a significant contribution to energy-related emissions, thus highlighting the linkages between the water sector, the energy sector, and food systems. These results confirm Morera et al.'s (2016) and Siyal's (2022) observations on the "hidden" carbon prices inherent in irrigation-intensive agriculture. In addition, recent systems approaches have indicated that it is possible to achieve major emission reductions while sustaining agricultural productivity through optimal management of the water-energy-food pillar, especially in the context of Pakistan's agricultural sector (Iqbal et al., 2026).

In particular, the fact that the region is centered on Okara becomes quite pertinent, especially when noting that the Punjab region is under substantial pressure due to climatic changes, groundwater depletion, and increased costs of production. As emphasized by Iqbal (2025), climate change is a serious threat to sustainability and human development associated with Pakistan, especially when it comes to agriculture, among many other affected areas. It appears from the findings that without addressing specific strategies for environmental control, increased crop intensification would contribute to environmental degradation.

In addition to its relevance to environment-based matters, its relevance to matters relating to society and the economy cannot be overlooked. Aslam (2025) illustrates that both water scarcity and energy crisis have a positive influence on household food security in rural Punjab; hence, carbon-based food systems have a potential indirect influence on heightened vulnerability. In addition to that, both gender-based factors of water insecurity, as proved by Khalid et al. (2024), have a negative influence on women.

The findings further buttress the need for the intervention of agricultural policies to ensure the adoption of climate-resilient agricultural technologies, precision application of fertilizer, energy-saving irrigation systems, and agricultural extension services. Enhancing agricultural extension services, as suggested by Kamal et al. (2022), would play a pivotal part in the application of low-carbon technologies, as well as increasing the adaptive capacity of the agricultural sector. Moreover, taking the carbon footprint of the agricultural sector into consideration could help make the agricultural sector compatible with the future climate goals of the world.

Therefore, this study contributes to the small body of empirical research on crop-specific carbon footprints in Pakistan and offers a local evidence base for climate policy and sustainable agricultural development. The findings, therefore, emphasize emission hotspots in the production of potatoes and maize, hence providing actionable emissions reduction insights while protecting productivity and food security in the Punjab.

CONCLUSIONS AND RECOMMENDATION

The key conclusion of this paper is that climate change is already impacting agricultural production in developing countries, and the sector is generally more vulnerable than other economic sectors. The increased levels of GHG, due to intensive fossil fuel burning, have risen and brought added pressures on crop production systems. Carbon footprint analysis offers a useful framework for assessing the CO_2 emissions linked with agricultural inputs, while water footprint assessment underlines the key function of water availability in identifying crop productivity, specifically for potato and maize. The main purpose of carrying out this research work is to estimate the carbon footprint, water footprint, and profitability of potato and maize production in District Okara. In this regard, primary data is gathered from 240 potato and maize growers by making use of a structured questionnaire. Being the backbone of Pakistan's economy, it is estimated that agriculture contributes around 19.5% to GDP, while over 42% of total employment is related to agriculture. Around 63% of rural households are dependent on agriculture either directly or indirectly. Crops like wheat, rice, cotton, sugarcane, potato, and maize are key crops of Pakistan, contributing largely to food security at a national level. The data shows a great difference in carbon and water footprint for different sizes of farms. The carbon footprint value was measured to be highest for medium farmers (549.26 kg CO_2-eq per acre), followed by large farmers (479.12 kg CO_2-eq per acre) and then for small farmers (476.76 kg CO_2-eq per acre). Also, there is a difference in water productivity for different sizes of farms. Large farms have efficiency in water utilization (7.50 kg per m^3) compared to medium (6.90 kg per m^3) and small farms (6.21 kg per m^3). Socioeconomic factors such as age, level of education, experience in farming, family size, and land size had important influences on production, adoption, and efficiency of resource utilization. Although experienced farmers were found to have effective management practices, small-scale farmers were restricted in terms of their land, savings, risk-taking ability, and adoption of modern technological advancements. Education levels among farmers were low, thus further restraining them from using improved agricultural practices. The findings, therefore, show that potato and maize cultivation are economically viable in District Okara, but there is much room for reduction in energy intensity and fertilizer application. Improved irrigation efficiency, renewable energy use, fertilizer optimization, farmer education, and extension services are key to carving out a carbon and water use reduction strategy with negligible trade-offs on profitability at farm gates. As such, policy support should focus on sustainability and productivity enhancement, including resilience in agricultural systems at small and medium-scale farming levels under shifting climatic conditions.

The promotion of effective pesticides should be improved through broadcasting and multimedia communication channels to ensure that farmers use the best practices in controlling pests. Another common complaint by farmers is the lack of certified seeds. Poor-quality seeds are often distributed by private companies as well as the Punjab Seed Corporation. To overcome this problem, the Punjab Seed Corporation should increase its business to supply high-quality seeds, and the government should help farmers by supplying good seeds to 2-3 farmers in every village, who can then multiply them. Credit facilities are one of the most important factors that can help modernize agriculture. Many farmers in this region are dependent on commission agents who charge them high rates of interest because there are no formal credit institutions in the region. The government must introduce micro-credit programs and make loan facilities easily accessible to farmers. Farmers are eager to adopt modern agricultural tools, but their requirements are not being met. The public and private sectors must make efforts to develop farming infrastructure. Both the government and non-government institutions need to establish training nodes and encourage approaches that are carbon literate, water literate, energy literate, and knowledge literate. Agricultural sectors need to be informed and segmented based on research and education levels, with workshops and rural education centers providing training in reducing carbon footprints, water footprints, the use of water efficiently, and the reduction of greenhouse gas emissions. The policy focus should include carbon taxes for emissions, subsidies for efficiently using farming practices, and Alternative Use of inputs, reducing carbon but optimizing water use. Adoption of the latest technology, in conjunction with effective education support, provides the best opportunity for increased productivity along with sustainable use of the environment in the agricultural sector of the country of Pakistan.

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