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Carbon Footprint and Life-cycle Cost of Maize (*Zea mays* L.) Production at Conventional and Regenerative Agricultural Practices

Shahid Ibni Zamir[1], Mehboob Ellahi[2], Muhammad Sami Ullah[2], Faisal Mehmood[3*]

[1]Department of Agronomy, University of Agriculture Faisalabad.
[2]Nestle Pakistan Limited, Lahore.
[3]Department of Chemistry, University of Lahore, Lahore, Pakistan.
[*]Corresponding author: faisalmehmood186@gmail.com

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Abstract

This study aimed to assess and contrast the carbon footprint and total expenses associated with maize production using conventional and regenerative agriculture methods. Data collected from Al-Rehman Dairy farms in the Dunyapur region encompassed the period from 2022 to 2023. The primary focus of the data was maize production for grain, with a comparison of two distinct methods: conventional and regenerative. The research aims to analyze greenhouse gas emissions and expenses connected with grain maize production using life-cycle assessment and costing approaches. This analysis covers the entire process, starting from getting raw materials and agricultural production means, through maize cultivation, and concluding with grain harvesting. Under the no-tillage system (NTS), soil organic contents (SOC) in the 0–15 cm and 15–30 cm soil layers were notably higher compared to those under conventional tillage. Specifically, SOC concentration in the 15–30 cm layer was greater under NT than conventional tillage. This trend in SOC content across different soil depths mirrored the pattern observed in SOC concentration. No-tillage resulted in significantly elevated SOC content in the 15–30 cm soil layer compared to conventional tillage. Nitrogen fertilizer consumption was the main cause of greenhouse gas emissions. By implementing non-inversion tillage in conjunction with rice straw mulch and maintaining significant crop residues in the field, there is an increase in the storage of organic carbon. This results in a significant decrease in the carbon footprint of maize agriculture. Out of all the systems examined, conventional tillage had the maximum life-cycle costs/hectare.

Keywords: Maize, Carbon sequestration, Benefit-cost ratio, Carbon footprint, Economic cost analysis.

Introduction

Regenerative agriculture (RA) techniques aim to mitigate the adverse environmental impacts of agriculture, such as soil degradation in terms of physical properties and erosion, which ultimately diminish productivity. These techniques encompass practices like zero tillage, mulching, preserving residues, and implementing optimal crop rotation or intercropping (Smart and Bradford, 1999, Gibson, 2022). In zero tillage, soil preparation is kept to a minimum, merely sufficient to facilitate sowing. The practice of no-tillage dates back to the inception of agriculture and persisted until the advent of animal-drawn plows. However, zero tillage, grounded in scientific principles and serving as an alternative to conventional tillage, emerged in the 1940s following the discovery of hormonal herbicides, enabling farmers to manage weeds without resorting to cultivators. Agriculture stands as a significant contributor to various environmental threats, accounting for 23-37% of total greenhouse gas emissions attributable to human activity (Gibson, 2022, Xiong *et al*., 2017). Conversely, regenerative agriculture (RA) practices not only yield food but also enhance the ecosystem services of agricultural land, including carbon sequestration, pollution reduction, soil health improvement, emission reduction, biodiversity promotion, and enhanced water retention, thereby lowering the risk of flooding. Consequently, regenerative practices enable farmers to cultivate food profitably while simultaneously accruing environmental and social benefits (Preston, 2020).

Maize (*Zea mays* L.) holds a prominent position as one of the most vital crops globally. It claims the top spot in cereal production worldwide and ranks second, just behind wheat, concerning cereal crop acreage (ur Rehman *et al*., 2021; Farnia *et al*., 2015). Maize has the highest grain energy value compared to other cereals. It has major role in the livestock nutrition and the food sector, specifically in the manufacturing of flour, porridge, and maize starch (Murdia *et al*., 2016). Maize, despite having simple soil and crop needs, has a somewhat strong need for water and minerals (Abakemal *et al*., 2013). Traditionally, maize cultivation relies on conventional tillage methods involving plowing. However, escalating costs, soaring fuel prices, natural constraints, and environmental concerns have led to the increasing adoption of regenerative agriculture practices in modern maize production technologies. Typically, this involves reduced tillage employing various machinery for shallow soil cultivation instead of plowing. Alternatively, although less common, the no-tillage system is feasible, wherein seeds are sown into untilled soil using specialized seed drills (Subbaiah *et al*., 2016; Gibson, 2022). In order to protect the quality of soil and the ecosystem, it is essential to implement regenerative agriculture techniques, namely conservation tillage, which involves leaving a minimum of 30% of plant residues in the field (García-Lara and Serna-Saldivar, 2019).

Greenhouse gas emissions originate throughout the life cycle of agricultural products, commencing from raw material extraction and agricultural production means' manufacture, through to product usage and waste management (Holka and Bieńkowski, 2020). The carbon footprint (CF) method is commonly employed to evaluate life-cycle emissions (Garofalo *et al*., 2017; Morão and De Bie, 2019). In recent years, the CF indicator has gained popularity for its utility in endeavors aimed at curbing greenhouse gas emissions across various domains (Fuchsz and Kohlheb, 2015; Al-Behadili and El-Osta, 2015). Life-cycle assessment (LCA) serves as a valuable tool in recognizing the primary sources of GHG emissions in the maize production chain, aiding in the development of solutions for reducing emissions in crop production.

The hypothesis posits that regenerative agricultural practices might demonstrate a reduced carbon footprint and lower life-cycle expenses compared to conventional methods in maize cultivation. This research endeavors to evaluate and compare the life-cycle costs and carbon footprint of maize production between traditional and regenerative agricultural techniques. Through precise quantification of emissions at each stage of maize growth and examination of the financial implications associated with adopting regenerative methods, this study aims to provide valuable insights for farmers, policymakers, and stakeholders to make informed decisions regarding sustainable maize production systems. The primary aim is to assess whether transitioning to regenerative agriculture can significantly reduce the carbon and economic costs of maize cultivation, thereby enabling environmentally and financially sound choices for participants throughout the supply chain.

Materials & Methods

The objective of the study was to investigate the measurement of carbon footprint and the cost of life-cycle maize production using both conventional and regenerative farming approaches. It was conducted over two growing seasons in spring and autumn 2022 at Al-Rehman Dairy Farm in Dunyapur District, Bahawalpur has a latitude of 29°48'16.35"N and a longitude of 71°44'26.04"E or 29.804542 and 71.740567, respectively.

Experimental Soil

The research experiments were performed on sandy loam soil, with soil samples taken at depths of 0-15cm, 15-30cm, and 30-40cm manually using a soil auger before each experiment's sowing. All sub-samples were thoroughly mixed to obtain a representative soil sample, which underwent various physical and chemical analyses.

Mechanical analysis of experimental soil

The hydrometer method was employed to ascertain the percentages of sand, silt, and clay in the homogeneous soil mixture of the experimental area before commencing each experiment during the study. Soil texture was determined using the international textural triangular method (Wang *et al*., 2017; Moreno-Maroto and Alonso-Azcarate, 2022). A detail of the mechanical analysis was given.

Chemical analysis of experimental soil

All subsamples of the experimental soil from each plot of every experiment were blended until a homogeneous mixture was achieved. Chemical analysis of the soil for various elements was conducted using the specified method (Jackson, 2005).

Field research experiments

The field experiments were set up in a randomized complete block design (RCBD) at Al-Rehman Dairy Farm in Dunyapur during both the spring and autumn growing seasons of 2022.

Experiment Design and Management

Prior to establishing the trials, soil homogeneity tests were conducted at the sites in 2022, where maize was cultivated as the sole crop without any inputs. Soil samples were gathered from depths of 0-15cm, 15-30cm, and 30-40cm for analysis. Using the data obtained from the homogeneity test, each treatment was replicated three times. Conventional farming (Conv) and regenerative farming were juxtaposed side by side at each site, with all inputs kept uniform.

Carbon Footprint (CF) Assessment

To evaluate the carbon footprint of maize cultivation, a life cycle assessment (LCA) is commonly conducted. This entails analyzing inputs and outputs throughout the maize production process, encompassing energy usage, fertilizer and pesticide application, and other factors, to estimate the total greenhouse gas (GHG) emissions linked with the crop (Peter *et al*., 2017; Adams and McManus, 2019). In accordance with the International Organization for Standardization (ISO) standard (Purdy, 2010), the process of Life Cycle Assessment (LCA) consists of four distinct phases: (1) establishing the objective and scope, (2) gathering a comprehensive inventory of the life cycle, (3) evaluating the environmental impacts throughout the life cycle, and (4) interpreting the results obtained. The research objectives, functional units, and system boundaries were clearly defined during the initial phase. The Life Cycle Inventory (LCI) phase entailed collecting data on both the inputs and outputs of the system. LCIA encompasses the process of choosing impact categories, indicators, and characterisation models. It also involves linking inventory data with impact categories through classification and determining indicator values through characterization. The last phase involved examining results and formulating conclusions. The study included the entire production process, from the initial stages of tool making to the growing of maize, until the agricultural goods were prepared for sale. Standardized functional units were one hectare of maize crop area and one ton of grain. The life cycle inventory (LCI) for individual processes in the assessed system was based on maize agricultural resource consumption data from the researched farms. The determination of chemical emissions into the environment was based on input data, which led to the generation of output data. The Ecoinvent 3.0 database and TEAMTM (Tools for Environmental Analysis and Management, version 5.3) LCA modeling program assessed pesticide and agricultural machinery emissions. The IPCC and European Environment Agency methods were used to estimate mineral and organic fertilizer emissions. European Environment Agency criteria were used to measure fuel burning emissions in agrotechnical procedures. However, crop residue N2O emissions were calculated using IPCC methodology (Low *et al*., 2014). Soil organic carbon concentrations under no-tillage systems in the 0–15 cm soil layer and under no-tillage in the 15–30 cm layer was significantly higher compared to those under conventional tillage. In the 15–30 cm soil layer, SOC concentration under NT surpassed that under CT. The disparity in SOC content across different soil depths between CT and NT mirrored the trend observed in SOC concentration (Table 1). NT yielded notably higher SOC content in the 15–30 cm soil layer compared to the CT system and when compared with CT in the 15–30 cm soil layer.

The differences in carbon footprint (CF) values of maize output among the examined soil tillage methods were ascribed to the varying degree of agricultural input use. Higher greenhouse gas emissions in conventional tillage and reduced tillage were primarily due to increased mineral fertilizer usage compared to no-tillage, as revealed by inventory findings. Studies indicate that elevated nitrogen fertilization levels lead to a significant increase in GHG emissions during maize cultivation (Adams and McManus, 2019). Grassini and Cassman (2012) found that no-tillage with mineral fertilizer and cover crops reduced greenhouse gas (GHG) emissions by 6% and 42%, respectively. Polish researchers studied bioethanol maize cultivation. Maintaining crop residues and using non-inversion tillage greatly reduced greenhouse gas (GHG) emissions (Arrieta *et al*., 2018). Studies have shown that crop rotations with legumes can reduce maize's carbon footprint (Wang *et al*., 2015). Growing maize with 100 kg N ha^{-1} in rotation with legumes reduced carbon footprint and maintained productivity compared to 200 kg N ha^{-1} production.

By factoring in the sequestration of organic carbon (C) into the overall greenhouse gas (GHG) emissions associated with the life cycle of grain maize production, we were able to determine the net carbon footprint (CF net). The CF value decreased by 42.9% in CT, 72.1% in RT, and 78.3% in NT systems, as compared to the baseline. When greenhouse gas emissions are considered per functional unit of one ton, it becomes evident that integrating carbon sequestration is the most effective approach for reducing overall GHG emissions in NT and RT systems, resulting in reductions of 78.3% and 72.1%, respectively. The primary source of potential carbon footprint reduction lies in managing maize crop residues (straw) and cultivating cover crops. These practices lead to significant amounts of crop residues remaining in the field, which aids in reducing carbon losses and promoting carbon sequestration. Additionally, the use of organic fertilizers also impacts carbon storage in the soil of both conventional tillage and no-tillage areas. Existing literature underscores the C sequestration process importance in mitigating the emissions of GHG (Holka and Bieńkowski, 2020; Spokas *et al*., 2012). The C sequestration calculation method employed in this study was specifically tailored to the soil and climatic conditions of Denmark (Yamasaki, 2003). Given the close geographical proximity and environmental similarities between our region and Denmark, adopting a regionally focused approach to calculate soil carbon accumulation was deemed appropriate. Ko *et al*. (2017) noted that the outcomes obtained using this technique are comparable to those obtained using methods outlined by the IPCC. Within each system studied, the application of mineral fertilizers had a significant impact on the CF indicator, with values ranging from 79.4% for conventional tillage to 84.6% for no-till in the overall CF value. Production and usage of nitrogen fertilizers accounted for a substantial portion (ranging from 65.4% for CT to 68.1% for of the total carbon footprint. GHG emissions during soil cultivation and sowing were highest in the conventional tillage system, accounting for 9% of total emissions. This was primarily attributed to larger fuel consumption and machinery usage compared to the no-till system, which accounted for 6.1% of emissions. The grain harvest represented 5.7% in CT and 7% in NT. GHG emissions were minimally affected by other operations. According to a cradle-to-farm gate life-cycle analysis, 72% of greenhouse gas emissions in grain maize production can be attributed to nitrogen fertilizer (Gaussin *et al*., 2013). In addition to mineral fertilizers, the carbon footprint in maize production is also greatly affected by fuel use during field operations, as supported by prior research (Chong *et al*., 2016). Several researchers have observed that irrigation significantly adds to greenhouse gas (GHG) emissions in maize cultivation (Wimbadi and Djalante, 2020; Mann *et al*., 2002). Nevertheless, the implementation of irrigation techniques that result in increased crop yields can help reduce greenhouse gas (GHG) emissions, especially when combined with measures to prevent land-use change (Gerbrandt *et al*., 2016). In the process of grain maize production, the carbon footprint in CT and NT systems was primarily influenced by variations in total nitrogen fertilizer use. Applying a 5% difference in N fertilizer led to roughly 3.3% and 3.4% alterations in total greenhouse gas emissions for conventional tillage and no-till practices, respectively. The impact of fuel use was the second most prominent factor, although the influence of phosphorus and potassium fertilizers was comparatively lower. The indicator was least affected by alterations in the utilization of organic fertilizer and agricultural machinery.

Table 1. Soil organic carbon content mg/ ha

Soil depth (cm)	**CT**	**NT**
0-15 cm	10.4±0.12	10.6±0.45
15-30cm	13.5±0.78	15.5±0.87
30-40cm	8.5±0.67	10.9±0.54

Results

Conventional agriculture and regenerative agriculture represent two distinct approaches to cultivating crops like maize. Conventional agriculture prioritizes maximizing yields via synthetic fertilizers, pesticides, and monoculture systems, often emphasizing efficiency and profits without considering long-term soil or ecosystem health. In contrast, regenerative agriculture takes a holistic approach, aiming to restore and enhance soil and ecosystem health. It emphasizes cover crops, reduced tillage, and crop rotations to promote soil organic matter and biodiversity, creating a self-sustaining system that produces healthy food while improving environmental health. Conventional agriculture may lead to soil degradation and decreased yields over time due to lower soil organic matter and increased pest pressure. Meanwhile, regenerative agriculture can enhance soil health and fertility, resulting in higher yields and crop resilience against challenges like drought or pests. Furthermore, regenerative agriculture offers additional benefits such as reduced water usage, enhanced water quality, increased carbon sequestration, and improved wildlife habitat.

Soil health benefits

Regenerative practices in maize (corn) crop production can provide several benefits to soil health and fertility. These practices, which include reduced tillage, cover cropping, and the use of organic fertilizers, can result in some positive impacts on soil, including:

- Increased soil organic matter: Regenerative practices can increase the amount of organic matter in soil, which can improve soil structure, water-holding capacity, and nutrient availability.
- Improved soil fertility: The increased organic matter in soil can provide a source of essential nutrients for plants, resulting in improved soil fertility and crop productivity.

- Enhanced soil structure: Reduced tillage and cover cropping can help to improve soil structure, making it easier for roots to penetrate the soil and increasing the soil's ability to retain water and nutrients.
- Increased water-holding capacity: Soil organic matter can improve soil's ability to hold onto water, reducing water runoff and increasing water availability for plants.
- Reduced soil erosion: Reduced tillage and cover cropping can help to reduce soil erosion by increasing vegetation cover and improving soil structure.

Table 2. Soil physicochemical analysis

Parameters	Pre-Soil Analysis		Post-Soil Analysis	
	0-15 cm	15-30 cm	0-15 cm	0-30 cm
Clay %	15.75	16.35	15.75	16.35
Silt %	35.85	34.75	35.85	34.75
Sand %	48.40	48.90	48.40	48.90
Texture	Loam	Loam	Loam	Loam
Saturation Percentage %	40	35	37	35
Carbonates me L^{-1}	2.50	2.95	2.05	1.95
Bicarbonates me L^{-1}	7.75	8.25	5.17	6.15
Chlorides me L^{-1}	10.65	12.75	12.85	14.50
Sodium me L^{-1}	9.75	8.25	12.75	9.75
Calcium and Magnesium me L^{-1}	15.25	16.55	17.85	20.95
Electrical conductivity m^{-1}	4.50	3.97	4.80	3.97
pHs	7.80	7.5	7.65	7.70
me $100g^{-1}$ of Soil	10.25	9.25	29.25	27.28
Available N%	0.12	0.08	0.17	0.16
Available P%	0.02	0.01	0.08	0.07
Available K%	0.56	0.60	0.89	0.79
Total Carbon%	0.58	0.45	0.91	0.85
Organic Matter%	0.89	0.76	1.62	1.02
C/N Ratio	4.83	5.63	5.35	5.31

- Improved soil health: Regenerative practices can improve soil health by promoting the growth of soil microorganisms and increasing soil organic matter, leading to a more diverse and resilient soil ecosystem.

In conclusion, regenerative practices in maize crop production can provide several benefits to soil health and fertility, including increased soil organic matter, improved soil fertility, enhanced soil structure, increased water-holding capacity, reduced soil erosion, and improved soil health. The adoption of these practices can help to promote sustainable and environmentally friendly maize production and contribute to the overall health of agricultural landscapes, soil Analysis shown in Table 2.

Economic Assessment

The economics of adopting new agronomic practices is crucial for farmers, who carefully weigh the benefits and costs against their invested capital. They seek to mitigate potential risks when transitioning from old practices to new innovations or technologies. Economic analysis involves various components such as partial budgeting, variable costs, gross and net income, and benefit-to-cost ratio (BCR). The methodology for preparing partial budgeting and calculating other economic components follows the approach discussed in Chapter #3 of the An Economic Training Manual of CIMMYT, as well as Chapter #4 for determining marginal cost, marginal benefit, and marginal rate of return. Crop productivity was assessed using the method outlined by Dass *et al*. (2011). The BCR, representing the ratio of benefits to costs, determines whether costs outweigh benefits (if less than one) or benefits exceed costs (if greater than one) (Andoseh *et al*., 2014). Net income for Zero Tillage is $61,477 compared to $29,557 for conventional tillage. BCR stands at 1.67 for Zero Tillage and 1.31 for conventional tillage, as detailed in Table 3.

An economic evaluation of maize cultivation technologies focused solely on mechanized operations, estimating machinery prices, fuel consumption, labor wages, and other associated direct and indirect costs. Given the fluctuating prices, costs for fertilizer, herbicides, and seeds were not estimated. Herbicide and seed application rates remained consistent across all technologies. Diesel fuel costs were determined based on the price of reduced complex fuel and oil fixed for Average farmers. Direct costs encompassed expenses for machinery upkeep, repair, maintenance, fuel, oil, and labor wages. Indirect inputs, comprising activities related to agricultural enterprise management, division maintenance, and facility upkeep, were estimated to contribute 5-10% of direct costs. Value-added taxes were not factored into the costs.

Table 3. Benefit-Cost Ration (BCR)

Treatments	Gross income (Rs. ha^{-1})	Cost that varies (Rs. ha^{-1})	Net income (Rs. ha^{-1})	BC ratio
Regenerative Zero Tillage	152,635	91,158	61,477	1.67
Conventional tillage	124,215	94,658	29,557	1.31

Conclusions

The research findings indicate that using no-tillage practices, along with sufficient crop residues, significantly decreases greenhouse gas (GHG) emissions in maize cultivation. Irrespective of the method used for cultivating land, the application of mineral fertilizers is the main factor that affects the amounts of greenhouse gas emissions. In order to develop low-emission solutions, it is necessary to specifically address the dangers that are linked with the usage of nitrogen fertilizer. It is crucial to optimize fertilization and crop productivity levels in order to reduce raw material consumption in fertilizer manufacture and limit field emissions. Comprehensive assessments of crop production's environmental performance should include evaluations of both carbon footprint and life-cycle costs. In order to address the variations in natural conditions among various areas, it is crucial to do additional study on the ecological consequences of agricultural cultivation employing diverse tillage techniques, while taking into account the complete life cycle of the crops. It is advisable to include life-cycle costs in future research on the carbon footprint of crop production in order to build a stronger basis for comparing economic expenditures and greenhouse gas emissions across different tillage methods. To summarize, while conventional agricultural approaches may provide immediate increases in crop yields and financial gains, regenerative agriculture presents a more sustainable and environmentally benign method for maize production, resulting in long-term advantages for both the ecosystem and farmers.

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