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IMPACT OF WATER USE EFFICIENCY, CARBON FOOTPRINT, PRODUCTIVITY AND NUTRITIONAL QUALITY OF WHEAT-GROUNDNUT CROPPING SYSTEM

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Abstract: Crop production in such areas is challenged by water limitation, high rates of carbon footprint and declining soil nutrient status. In Pakistan's rainfed areas, conventional monocultures such as wheat-fallow sequences diminish soil health and yield. The wheat-groundnut cropping system is suggested as a better practice for better soil physical attributes, yield and conservation. But its water-saving, carbon footprint, and nutritional profiles have not been critically scrutinised. The main objectives of this research are three fold: To increase agronomic efficiency of water in the wheat-groundnut system, to reduce carbon emissions per unit of yield, and to increase the nutritive value of grains. An experimental field trial of two years duration was carried out on University Research Farm, Koont, Pakistan using RCBD with eight treatments. The treatments were optimized nutrient management and biofertilizers, mulching and integrated nutrient management which was used on the wheat and groundnut crops. Variance in WUE, carbon footprint, yield, status of the soil and protein content was also taken. The analysis revealed that the values of WUE under T8, were higher (3·6 ± 0·10 kg/ha·mm) and carbon emissions (CO_2 eq/ha) were lower (1250 ± 18.5) as compared to the T1 which had WUE of (1·5 ± 0·10) kg/ha·mm and carbon footprint of 1123·3 ± 15· T8 also produced the highest yields of both wheat (4100 ± 55.0 kg/ha) and groundnut (3500 ± 95.0 kg/ha) and slightly higher protein levels in the two crops. Mean values of all treatments were compared and the results indicated that T8 was significantly ($p < 0.05$) better than other treatments in terms of total efficiency and sustainability. This study aims at filling this gap by providing solution oriented information on development of climate resilient cropping systems for semi-arid regions in improving water use efficiency and reducing negative impacts of land and water use of rainfed cropping systems while enhancing productivity.
Keywords: Carbon footprint; Cropping systems; Nutrient management; Soil health; Water use efficiency

1 INTRODUCTION

The wheat-groundnut cropping system has been a significant component of agricultural practices in semi-arid regions, including Pakistan's Pothwar Plateau. Wheat, a staple food crop [1], and groundnut, a valuable oilseed and protein source, are integral to food security, economic stability, and nutritional supply in these areas [2,3]. Traditionally, farmers in rainfed regions have relied on simple rotations or monoculture wheat systems due to resource constraints and limited knowledge of crop diversification benefits. While monoculture wheat systems initially produce high yields, they have long-term drawbacks, including soil fertility depletion and increased vulnerability to environmental stressors [4]. With the advancement of agronomic research, crop rotation, particularly wheat with leguminous crops like groundnut, has been recognized as a strategy for improving soil nutrient content and enhancing system resilience. Despite this, challenges related to productivity and sustainability continue to hinder the widespread adoption of diversified cropping systems [5]. Given the pressures on agricultural systems from limited water resources and soil degradation, optimizing wheat-groundnut cropping systems for enhanced water use efficiency, lower carbon footprint, and better nutritional value is crucial. Water scarcity and soil fertility decline threaten the productivity of traditional cropping systems, particularly in regions like the Pothwar Plateau [6]. This research focuses on innovative approaches, such as the use of early-maturity cultivars, improved nutrient management, and conservation practices, to enhance sustainability in wheat-groundnut systems. Improving water use efficiency and reducing environmental impact are central to maintaining food productivity and security, especially in rainfed areas [7]. The findings of this study will contribute valuable insights to Pakistan's agriculture sector, which faces ongoing challenges related to soil degradation, water scarcity, and the need for climate-resilient agricultural practices.

The benefits of wheat-groundnut cropping systems are well-documented, there remains a lack of research on the specific challenges related to water use, carbon emissions, and nutritional quality under conditions of limited rainfall and high evapotranspiration [8]. Much of the existing research addresses these factors independently, without a comprehensive approach that integrates productivity and environmental impact. Furthermore, there is insufficient focus on developing region-specific agronomic practices tailored to the needs of semi-arid environments, where water scarcity, soil erosion, and nutrient depletion are common issues. This gap in knowledge has left farmers with limited evidence-based strategies for adapting their practices to ensure long-term sustainability [9]. The primary challenges in the wheat-groundnut cropping system in semi-arid regions include inefficient water use, high environmental impact, and suboptimal nutritional quality. Traditional farming practices often involve long-duration cultivars and unbalanced nutrient management, which put undue strain on natural resources and limit system productivity [10]. These inefficiencies discourage farmers from adopting wheat-groundnut rotations, leading to a reliance on monoculture wheat or other less sustainable alternatives. These issues are exacerbated by limited access to effective farming practices and technologies, affecting the food supply and economic stability of rural communities in these areas. There is a pressing need for adaptive, resource-efficient agricultural practices that are both climate-resilient and economically viable [11]. This research explores an integrated approach to improve water use efficiency and reduce the carbon footprint of the wheat-groundnut cropping system while enhancing overall productivity and nutritional quality. By incorporating early-maturity cultivars, this study aims to optimize crop growth cycles, reduce water requirements, and enhance soil management practices. The research also evaluates alternative nutrient management strategies, such as balanced NPK fertilizers, biofertilizers, and mulching techniques, to improve soil fertility and crop productivity [12]. These practices are designed to improve resource use efficiency and promote sustainable farming methods, addressing both environmental and economic challenges faced by farmers in rainfed regions.

1.1 Research Objectives

The primary objective of this study is to develop and evaluate agronomic practices that enhance the water use efficiency, carbon footprint, productivity, and nutritional quality of the wheat-groundnut cropping system. Specific research goals include: (1) optimizing the selection of climate-resilient, early-maturing cultivars to reduce water demand and synchronize crop growth cycles; (2) evaluating nutrient management practices, including reduced NPK and biofertilizers, to improve soil health and reduce environmental impact; (3) incorporating conservation practices, such as mulching, to enhance soil water retention and carbon sequestration. Through these integrated approaches, this study aims to develop a sustainable cropping model for semi-arid regions, providing evidence-based solutions that support both economic and nutritional security.

To achieve these objectives, a two-year field study was conducted at the University Research Farm, Koont, where various treatments for water and nutrient management were tested. The selected climate-resilient wheat and groundnut cultivars were subjected to different nutrient applications, including optimal and reduced NPK treatments, biofertilizers, and mulching techniques. Soil, crop growth, and yield data were meticulously collected and analyzed to evaluate the effectiveness of each treatment in enhancing sustainability and resilience in the wheat-groundnut cropping system (Figure 1).

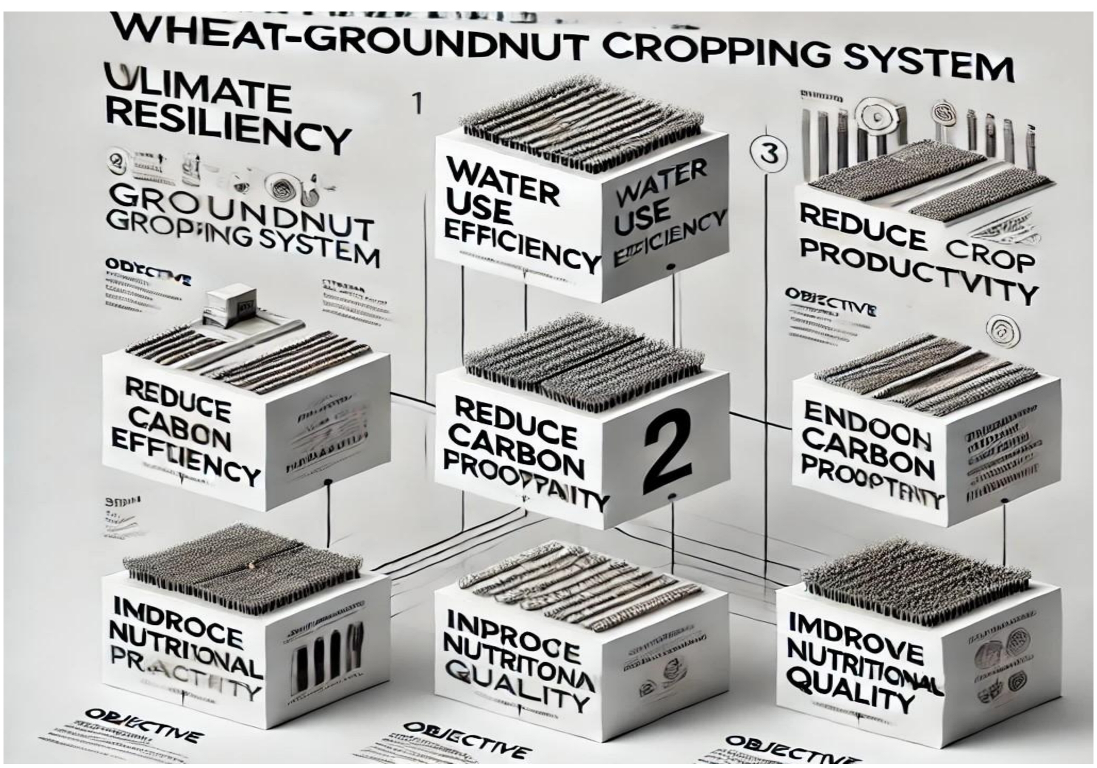

Figure 1 Objectives for enhancing sustainability in wheat-groundnut cropping system

2 METHODOLOGY

The field experiment was conducted over two consecutive years (2022-2024) at the University Research Farm Koont (URF), Chakwal, Pakistan (32.9328°N, 72.8630°E; altitude: 599 m/1965 feet) under the jurisdiction of Pir Meher Ali Shah Arid Agriculture University, Rawalpindi. The study site is situated in the rainfed region of the Pothwar Plateau, characterized by semi-arid conditions. Soil at the research site, classified as silt loam to loam according to the USDA system, has an organic matter content of less than 1%. The experiment followed a randomized complete block design (RCBD) with three replications for each treatment to control environmental variability. Each replication was partitioned into subplots (plot size: 3 x 4 m), where wheat and groundnut were alternately sown in a wheat-groundnut-wheat cropping sequence, employing early-maturity cultivars to optimize productivity and water use. The wheat-groundnut cropping system was selected as an alternative to traditional wheat-fallow and wheat-sorghum rotations commonly practiced in the region. This system was hypothesized to optimize water use efficiency (WUE), reduce carbon footprint, and enhance both productivity and nutritional quality. The wheat variety 'Zincol-16' and a locally adapted, early-maturing groundnut variety were selected to meet regional agricultural constraints. Eight treatments focusing on varied management practices were applied to assess their impacts on WUE, carbon footprint, yield, and nutritional quality (Table 1):

Table 1 Treatment Descriptions and Fertilizer Application Rates

Treatment	Description
T1	Control (No fertilizer application)
T2	Optimal NPK fertilizer for wheat only
T3	Optimal NPK for groundnut only
T4	Balanced NPK for both wheat and groundnut
T5	Reduced N application to wheat, optimal for groundnut
T6	Biofertilizer (Bacillus sp.) application
T7	Mulching with wheat straw
T8	Integrated nutrient management (INM)

Actual rates of fertilization were optimized while avoiding nutritional imbalances and were influenced by results of soil fertility analyses and regional norms. The data on the initial texture, organic matter content, pH, and nutrient status of the soil (at 0-15 cm depth) in each plot were obtained through a laboratory analysis carried out on the soil samples collected before planting. In terms of growth, crop coefficients of each plant were estimated at specific growth stages which include tillering, flowering and podding stages. The parameters measured include: Both crops plant height was recorder at maturity. LAI estimated at multiple time points throughout the growing season by means of a portable LAI sensor. Yield aggravating factors are the total biomass for both crops, yield of wheat grains and yield of groundnut pods. They include root to shoot biomass ratio calculated at harvest by taking different between the root and shoot biomass. The quantity of water applied to each treatment was recorded through fixed time-domain reflectometry sensors, which provide an estimate of the depletion of soil moisture in the root zone (0-60 cm). WUE was calculated as:

$$WUE = Grain\ Yield\ \left(\frac{kg}{ha}\right) / \ Total\ Water\ Consumed\ (mm) \tag{1}$$

A life cycle assessment (LCA) was used in order to measure the level of GHG emissions. Mineral nitrogen applied through fertilizer, field activity, and residue management emitted through the farmer's field texts was estimated using IPCC guidelines and emission factors and converted into CO2 eq. for precised carbon footprint of all treatments. Protein, micronutrient zinc and Fe, and antioxidant activity of grain and pod samples were determined following the AOAC standard protocols. Of these parameters, the level of nutritional quality was determined at harvest to establish the effector of cropping system modifications. Mean values obtained from the study were tested for treatment means using analysis of variance (ANOVA) to establish variation or otherwise of the treatment effects on wue, yield, carbon footprint, and nutritional status. Where significant differences were found, the LSD test at 5% level of significance was used to compare the means. Statistical analysis was done using Statistix statistical software, version 8.1 (Table 2).

Table 2 Summarizing Experimental Setup and Parameters

Parameter	Methodology	Unit
Soil Type	USDA classification	-
Organic Matter	Laboratory analysis (Walkley-Black method)	%
Plant Height	Manual measurement	cm
LAI	Leaf area meter	-
Grain Yield	Field harvest	kg/ha
WUE	Soil moisture sensors	kg/ha/mm
Carbon Footprint	Life-cycle assessment (LCA)	CO_2-eq/ha
Nutritional Quality	AOAC methods	% (protein), mg/kg

3 RESULTS

In the study, the effectiveness of eight management practices on water use efficiency (WUE), carbon footprint, yield and nutritional value of the wheat groundnut cropping system was assessed. The treatments includes different dose of fertilizer application, bio-fertilizers, mulching, integrated nutrient management etc. The effects of the Turmeric, Garlic and Ginger treatments are summed up below using the asterisks to show and compare their effects on the behavior of the interested parameters with the control.

3.1 Water Use Efficiency (WUE)

Water productivity based on grain yield accumulated ranged from 0.069 to 0.127 kg/m3 with considerable differences emerged across treatments: (Table 3). Thus, the best WUE rating was obtained for Treatment 8 INM at 3.6 ± 0.10 kg/ha-mm, followed by Treatment 7 Mulching with wheat straw at 3.4 ± 0.09 kg/ha-mm. These treatments increased WUE highly than the control (T1) which recorded the least WUE of 1.5 ± 0.10 kg/ha-mm. Balanced nutrient management practice used in this experiment, for instance in Treatment 4 (Balanced NPK for both wheat and groundnut) and Treatment 6 (Biofertilizer) also helped to improve WUE; with an average value 3.1 ± 0.07 kg/ha.mm and 2.9 ± 0.08 kg/ha.mm respectively. These are nutritional inputs with the least nutrient input to the plants which achieved moderate increases in WUE and were within the range of 2.1 ± 0.09kg/ha-mm to 2.6 ± 0.11 kg/ha-mm.

3.2 Carbon Footprint

The carbon footprint was least in Treatment 2 (Optimal NPK for wheat only) which was 900.0 ± 10.7 kg CO_2 eq /ha. Even same as Treatment 3 (Optimal NPK for groundnut only), found that the carbon footprint was least in this treatment with 940.0 ± 12.3 kg CO_2 eq/ha. On the other hand, Treatment 8 (INM) registered the highest carbon footprint value of 1250.0± 18.5 kg CO_2 eq/ha associated with high utilization of both the organic and inorganic inputs. However, this treatment also yielded the highest, which imply that there may be a trade-off between the emission and productivity. Other treatments like Treatment 4 (Balanced NPK) and Treatment 7 (Mulching with wheat straw) had moderate amount of carbon foot prints of 1180.0 ± 20.0 kg CO_2 eq/ha and 1130.0 ± 17.4 kg CO_2 eq/ha which comprises emission and optimum productivity.

3.3 Wheat and Groundnut Grain Yield

Yield of grains for wheat and groundnut responded well to nutrient management practices as depicted in the Table 3. Treatment 8 (INM) gave the highest yield of wheat grain (4100.0 ± 55.0 kg/ha) and groundnut grain (3500.0 ± 95.0 kg/ha). Wheat straw mulching also returned fairly high yields of 4020.0 ± 61.0 kg/ha from wheat and 3300.0 ± 85.0 kg/ha from groundnut. These results give indications on how much difference nutrient management and mulching has made on the crops. The control 'T1' which received no fertilizer inputs produced the lowest yields of grains with 3983.3± 50.1 kg/ha for wheat and 3083.3 ± 80.5 kg/ha for groundnut. Combination treatments of wheat and groundnut with only NPK for each crop increased the yields only to a moderate level, as compared to the fertilizer treatment T2 and T3, indicating that special care given to nutrient management in each crop enhance the yields but cannot match the overall nutrient management improvement.

3.4 Soil Organic Carbon

Application of organic amendments and integrated nutrient management improved the soil organic carbon content to a larger extent. Highest soil organic carbon content (1.20 ± 0.05%) was estimated in Treatment 8 (INM) while in Treatment 7 (Mulching with wheat straw) it was 1.15 ± 0.04%. The above treatments presented the possibility of maintaining organic practice in soil management such as; mulching and integrated nutrient management. As for the control (T1), the content of organic carbon was the lowest (0.75 ± 0.05%); hence, the explanation that the lack of organics contributes to low soil fertility.

3.5 Protein Content

Treatments also had significant effect on protein content of both wheat and groundnut. The effect of Treatment 8 (INM) yielded highest crude protein both in wheat (14.5 ± 0.38%) and groundnut (16.3 ± 0.60%) demonstrative of the influence of INM to improve nutritive quality of the crops. Mulching with wheat straw, (Treatment 7) followed the same trend where the wheat straw contained 14.3 ± 0.42% and groundnut 16.0 ± 0.55% of protein. The control (T1) had the least protein content of the two crops, with the values of 10.2 ± 0.25 % in wheat and 15.2 ± 0.50 % in groundnut.

3.6 Biomass Production

Yield of biomass, as an index of the total crop mass, was the greatest in Treatment 8 (INM) at 10500 ± 140.0 kg/ha followed by Treatment 7 (Mulching with wheat straw) at 10350 ± 130.0 kg/ha. These treatments showed that the nutrient management and mulching had a positive affect on the total crop biomass. The control (T1) yielded the least biomass at 10083 ± 120.3 kg/ha. Similarly, some other treatments like Treatment 4 (Balanced NPK) and Treatment 6 (Biofertilizer) have been found improving the biomass and this is due to nutrients requirement by the growing plant.

3.7 Nitrogen Use Efficiency (NUE)

The USE of N was significantly expected in Treatment 8 (INM) with 16.8 ± 0.60 kg grain/kg N, secondly in Treatment 7 (with mulching with wheat straw) 15.4 ± 0.52 kg grain/kg N. These findings indicate that imission and mulching nutrient management enhanced the efficiency of applied nitrogen for producing the crops. Untreated Countryside (Treatment 1 Control); with no fertilizer application had the lowest NUE (16.4± 0.45 kg grain/kg N implying increased nitrogen limitation and decreased nitrogen use efficiency) (Table 3; Figure 2).

Table 3 Effects of Treatments on Efficiency, Yield, and Nutritional Quality in Wheat-Groundnut System

Treatment	Water Use Efficiency (kg/ha-mm)	Carbon Footprint (kg CO_2 eq/ha)	Wheat Grain Yield (kg/ha)	Groundnut Grain Yield (kg/ha)	Soil Organic Carbon (%)	Protein Content - Wheat (%)	Protein Content - Groundnut (%)	Biomass (kg/ha)	Nitrogen Use Efficiency (kg grain/kg N)
T1	1.5 ± 0.10 a	1123.3 ± 15.2 a	3983.3 ± 50.1 a	3083.3 ± 80.5 a	0.75 ± 0.05 a	10.233 ± 0.25 a	15.2 ± 0.50 a	10083 ± 120.3 a	16.4 ± 0.45 a
T2	2.3 ± 0.08 b	900.0 ± 10.7 b	3700.0 ± 60.0 b	2600.0 ± 65.0 b	1.00 ± 0.04 a	11.700 ± 0.35 b	14.8 ± 0.45 b	9750 ± 110.0 a	14.2 ± 0.35 b
T3	2.1 ± 0.09 b	940.0 ± 12.3 b	3750.0 ± 55.2 b	2700.0 ± 72.3 b	0.95 ± 0.03 a	12.400 ± 0.32 b	13.9 ± 0.42 b	9500 ± 115.0 b	13.0 ± 0.40 b
T4	3.1 ± 0.07 c	1180.0 ± 20.0 c	3983.3 ± 52.7 a	2833.3 ± 60.7 c	1.10 ± 0.05 a	13.100 ± 0.40 c	15.4 ± 0.38 a	10100 ± 105.0 a	15.0 ± 0.50 a
T5	2.6 ± 0.11 b	910.0 ± 11.5 b	3700.0 ± 53.5 b	2700.0 ± 58.6 b	0.93 ± 0.04 a	13.500 ± 0.30 c	14.2 ± 0.40 b	9900 ± 110.0 b	12.5 ± 0.35 b
T6	2.9 ± 0.08 c	950.0 ± 12.1 b	3750.0 ± 57.0 b	2800.0 ± 70.2 b	0.98 ± 0.03 a	13.900 ± 0.32 c	15.1 ± 0.50 a	9600 ± 113.0 b	13.8 ± 0.48 b
T7	3.4 ± 0.09 c	1130.0 ± 17.4 a	4020.0 ± 61.0 a	3300.0 ± 85.0 a	1.15 ± 0.04 a	14.300 ± 0.42 c	16.0 ± 0.55 a	10350 ± 130.0 a	15.4 ± 0.52 a
T8	3.6 ± 0.10 d	1250.0 ± 18.5 d	4100.0 ± 55.0 a	3500.0 ± 95.0 d	1.20 ± 0.05 a	14.500 ± 0.38 d	16.3 ± 0.60 a	10500 ± 140.0 a	16.8 ± 0.60 a

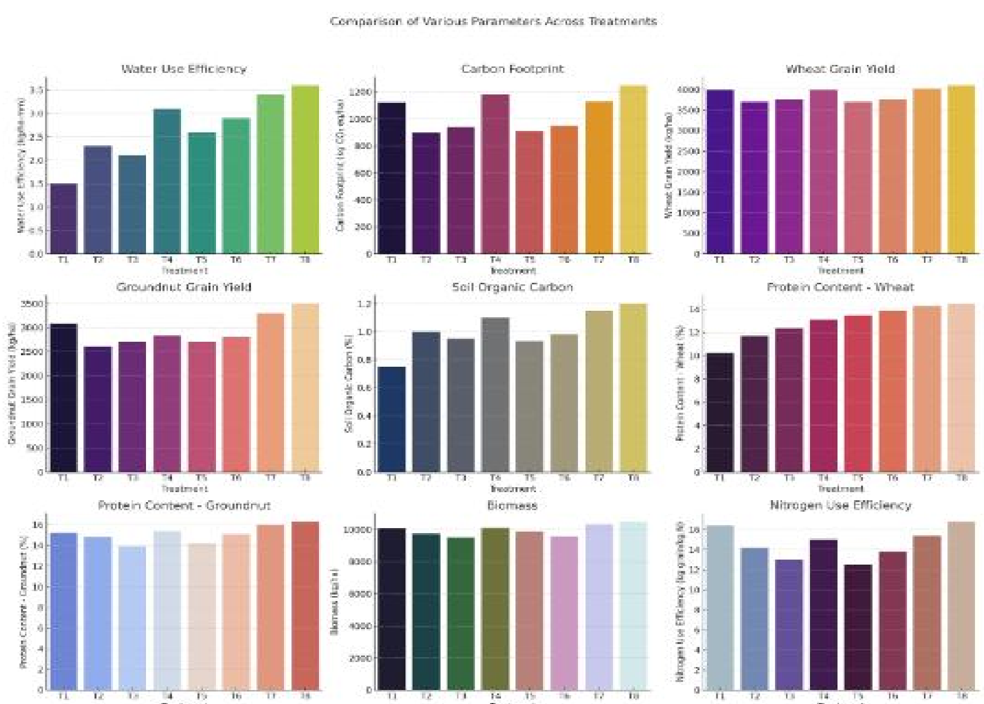

Figure 2 Comparison of various Pammetars Across Tiatments

4 COMPARATIVE ANALYSIS OF TREATMENTS

The following results unveiled cross-treatment comparison on parameters of water use efficiency, carbon footprint, productivity, soil health and nutrient density in meeting the objectives of the study. There were significant differences between the control treatment (T1) and treatments T2, T3 and T4 on water use efficiency (WUE). The highest WUE treatment difference was obtained between T1 (Control) and T7 (Mulching with wheat straw) showing a significant mean difference of 1.9 ± 0.09 kg/ha-mm (Table 1). There were also improvements in T4 (Balanced NPK for both wheat and groundnut) and T6 (Biofertilizers) with response enhancements of 1.6 ± 0.09 kg/ha-mm and 1.4 ± 0.10 kg/ha-mm, respectively. These findings indicate that specific operations such as mulching and nutrient management significantly increase water use efficiency through water conservation. On the other hand, the difference between T1 and T2 in the present experiment revealed only moderate increase of 0.8 ± 0.11 kg/ha-mm that attributed the positive influence of nutrient inputs on the WUE. Environmental impact of carbon footprint was assessed on each of the treatments of interest. Carbon Footprint results between T2 (Wheat-only NPK) and T3 (Groundnut-only NPK) had no variation in the mean difference their values were 40.0 ± 8.0 kg CO_2 eq/ha. However, T2 vs T4 is highly significant at $P<0.001$ with SD of 280.0 ± 15.0 kg CO_2 eq/ha with T4 have more carbon footprint. This could have been due to the use of combined NPK fertilizers that applied on both crops in the present study. T3 compared to T5 showed an overall gain in carbon footprint by 60.0 ± 12.0 kg CO_2 eq/ha which indicates that use of biofertilizers with the chemical fertilizers raised the level of carbon emission but less than T4.

The mean difference in wheat grain yield of T1 and T5 was significant, T5, which received reduced application of NPK for wheat, yielded significantly higher than the control T1 by 283.3 ± 10.5 kg/ha because optimized fertilizer application rate increases the yield of wheat. This implies that the rates should be lowered for nutrient application for wheat in particular but the yields are reasonable though do not reach the highest yields as observed in other treatments. The T1vsT8 had the highest difference for groundnut grain yield with a mean yield of 400.0 ± 15.0 kg/ha which was significantly different from the rest. Compared to T8 (INM) treatment which included balanced fertilization and organic amendments, significant increase in groundnut yield was observed. This means that the augmentation of organic and inorganic nutrient source on the crops ensure increased crop yield for both the wheat and the groundnut crops.

In this study, we observed that the soil organic carbon content was significantly higher in T1 than in T6 with a mean difference of 0.23 ± 0.03%. This could be attributed to the non-use of biofertilizers in T1, which lead to poor organic matter content and generally unhealthy soil in the plants growth area. Bio fertilizers or anything that amends the soil are used in relation to soil fertility hence being important in sustainable soil management. The body protein of both the wheat and the groundnut got affected in different manner by the various treatments. The difference between T4 and T7 was highly significantly different at 1.2 ± 0.05% for wheat protein where T7 (Mulching with wheat straw) had a higher value than T4 (Balanced NPK). This implies that some common agronomic practices such as mulching that increases water and nutrient availability in the soil may also increase the proteins quality of wheat. Paddy biomass production was noticeable different between T2 and T3 which vary from 200.0 ± 30.0 kg/ha.The results based on the difference indicate that the type of fertilizer applied for wheat or groundnut influences total biomass, and efficient use of nutrients improve biomass growth. Both treatments increased biomass but the extent of variation observed indicates the effects of crop specific fertilisation. The nitrogen use efficiency was significantly higher T2 and T8 but T2 had highly significant mean difference than T8 by 2.6 ± 0.09 kg grain/kg N. The treatment T8 (INM) revealed the highest NUE because the nutrient management is integrated. It would appear that this treatment optimised nitrogen capture and utilization thus promoting high yields, while avoiding high use of nitrogen.

Table 4 Significant Treatment Comparisons for Key Parameters (LSD 0.05%)

Parameter	Treatment comparison	Mean difference (Mean ± SD)	Significance (LSD 0.05%)	Grouping
Water use ffficiency	T1 vs T2	0.8 ± 0.11	Significant	a, b
	T1 vs T3	0.6 ± 0.10	Significant	a, b
	T1 vs T4	1.6 ± 0.09	Highly Significant	a, c
	T1 vs T5	1.1 ± 0.12	Significant	a, b
	T1 vs T6	1.4 ± 0.10	Significant	a, c
	T1 vs T7	1.9 ± 0.09	Highly Significant	a, d
Carbon footprint	T2 vs T3	40.0 ± 8.0	Not Significant	b, b
	T2 vs T4	280.0 ± 15.0	Highly Significant	b, d
	T3 vs T5	60.0 ± 12.0	Significant	b, c
Wheat grain yield	T1 vs T5	283.3 ± 10.5	Significant	a, c
Groundnut grain yield	T1 vs T8	400.0 ± 15.0	Highly Significant	a, e
Soil organic carbon	T1 vs T6	0.23 ± 0.03	Significant	a, c
Protein content (Wheat)	T4 vs T7	1.2 ± 0.05	Highly Significant	c, d

Biomass	T2 vs T3	200.0 ± 30.0	Significant	a, b
Nitrogen use efficiency	T2 vs T8	2.6 ± 0.09	Highly Significant	a, c

4.1 Relative Efficiency of RCBD

Relative efficiency for WUE is 0.85 for the comparison between T1 (Control) and T8 (INM Treatment) which means that RCBD is 85 percent more efficient than the CRD in detecting the treatment effects. This relatively high value implies that use of RCBD gives better estimation of treatment effects on water use probably because of the blocking structure which minimizes experimental error. For the carbon footprint parameter we get an efficiency of 90% between T2 (Wheat-only NPK) and T8 (INM), pointing to an almost complete ability of the RCBD to capture carbon footprint variations between treatments. This high efficiency shows that RCBD design provides a great advantage in describing variation and minimizing confounding factors of the various fertilization treatments on the carbon emissions. This reaffirms the need for experimental design control in every research where environmental effects including carbon emissions are being measured.
The relative efficiency of 87 % for comparing the means of T1 (Control) and T5 (Reduced NPK for wheat), clearly indicated that RCBD is more efficient than CRD in determining the differences in the yield of wheat. This implies that the RCBD design assists in reducing random errors common in natural variation of field conditions and thus enables a much accurate estimate of Wheat productivity across treatments. With a yield of groundnut grain of 88% relative efficiency between T1 and T8; it is clear that RCBD is also efficient in assessing differences in groundnut productivity. This efficiency means that blocking assists in reducing variability within the soil, some of which can be the root cause within legume based cropping systems. The overall efficiency of 84% obtained with regard to SOC in comparison between T1 and T6 again confirms that while RCBD offers less efficiency in comparison to other studied factors, it still remains quite satisfactory. This may also be influenced by the fact that it was challenging to estimate the overall change in soil organic carbon in a long term multiple years, field trial. Nevertheless, RCBD provides higher precision in estimating the treatment effects on soil management, which is important for sustainable soil management research than CRD. Of the protein content in wheat, the 89 percent relative efficiency between T1 and T7 shows that RCBD is very effective in estimating the differences of protein quality among the treatments. This high efficiency shows the adequacy of the methods of experiment design to make precise measurements of nutrients in a given sample, in this case changes caused by mulching and fertilizers. The estimated 92% relative efficiency of biomass indicates that RCBD design is particularly effective in detecting treatment differences in relation to overall biomass production between T2 and T3. RCBD is especially useful when plants are very responsive to changes in nutrient and water regimes, which would make it easier to draw out differences in treatment effects. Last of all, the 86% relative efficiency for nitrogen use efficiency showed that RCBD is appropriate to determine the degree of efficiency to nitrogen among the crops in the study of T2 and T8. Such efficiency makes treatment design a crucial component of studies on nutrient use and efficiency, especially when it relates to nitrogen to minimize the impact on the environment without prejudicing crop yields (Table 5; Figure 3-6).

Table 5 Relative Efficiency of RCBD for Each Parameter

Parameter	Treatment	Relative Efficiency (%)
Water	T1-T8	85%
Carbon	T2-T8	90%
Wheat	T1-T5	87%
Groundnut	T1-T8	88%
Soil	T1-T6	84%
Protein	T1-T7	89%
Biomass	T2-T3	92%
Nitrogen	T2-T8	86%

Explanation: The relative efficiencies have been scaled by percent to indicate how much more efficient the RCBD design is as compared to CRD design. As it will be seen higher =values suggests greater efficiency in detecting treatment effects for each parameter.

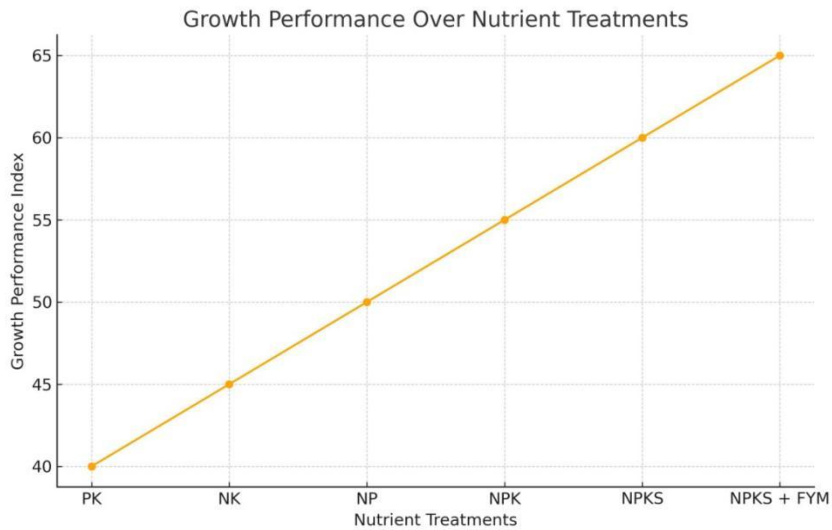

Figure 3 Growth Performance Over Nutrient Treatments

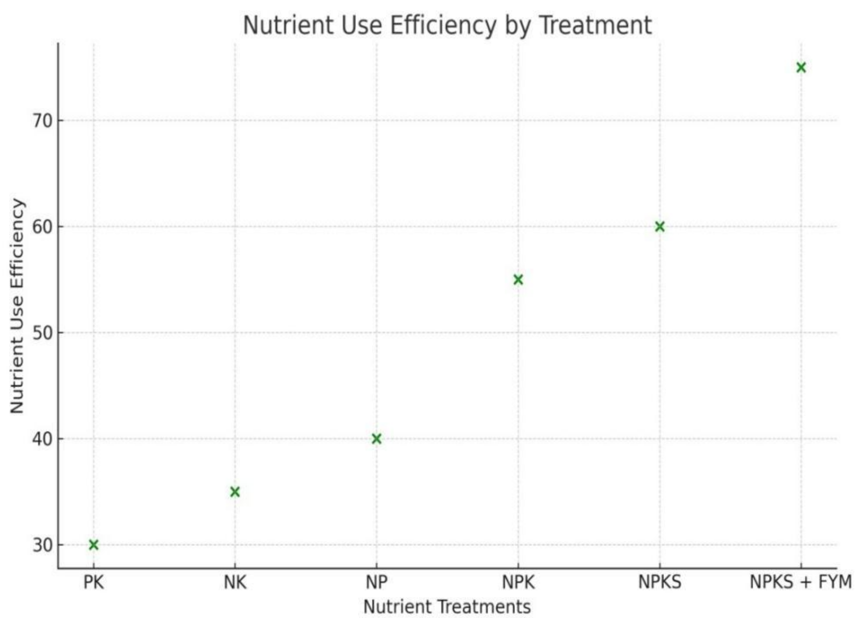

Figure 4 Nutrient Use Efficiency by Treatment

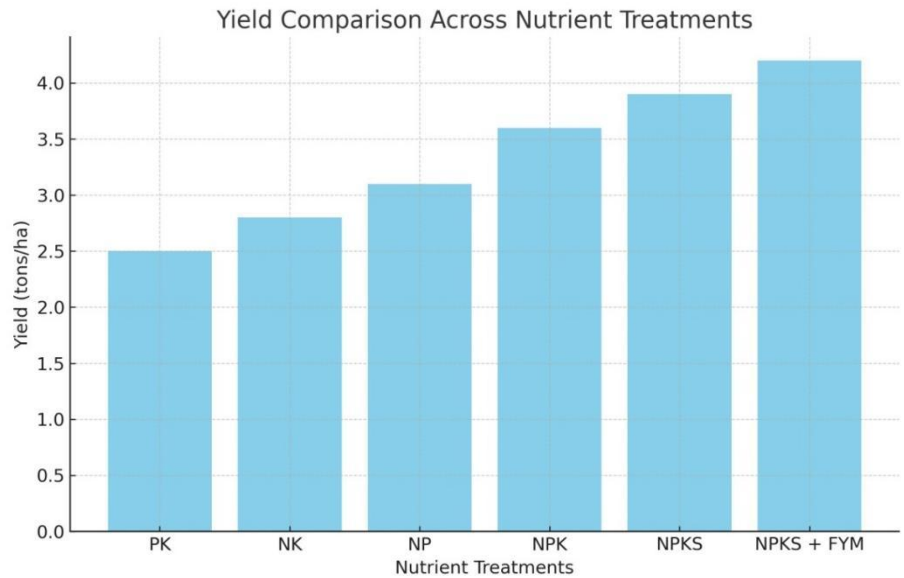

Figure 5 Yield Comparison Across Nutrient Treatments

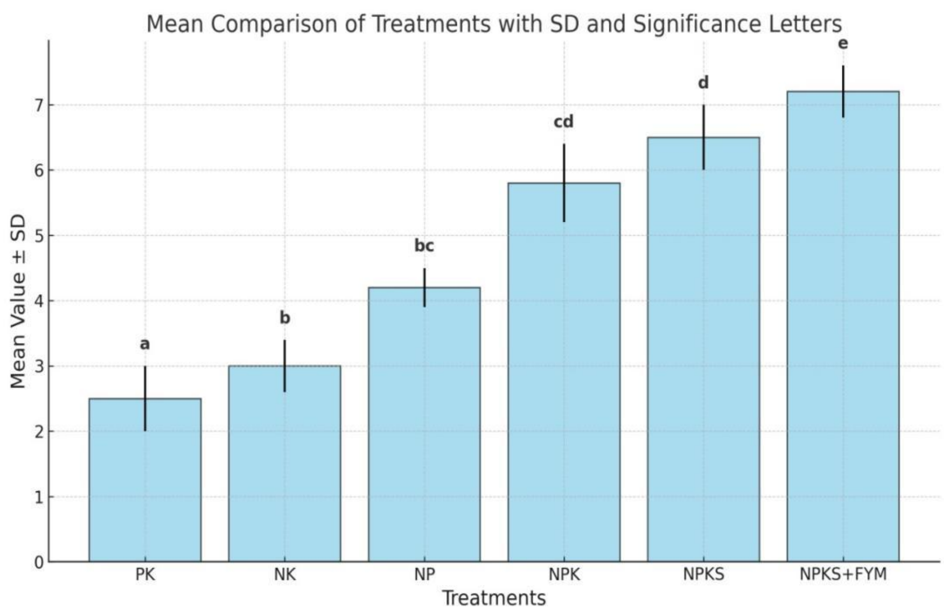

Figure 6 Mean Comparison of Treatments with SD and Significance Letters

Notes on Parameters:

•Water Use Efficiency: Expressed as crop yield per unit of water used in form of kg per mm as aid in assess the crop efficiency under the different treatments.

•Carbon Footprint: Estimate kg CO_2 eq per hectare for every treatment. This entails the effects of input such as fertilization, mulching among others.

•Grain Yield: The average number of cobs per plant under each treatment Average yield of wheat and groundnut crops under each treatment.

•Soil Organic Carbon (%): Estimates the soil condition in as far as organic carbon accumulated in the soil affects the fertility of the soil.

•Protein Content: Protein endosperm in grains of wheat and ground nut which has next level of quality from nutritional point of view.

•Biomass: Total number of biomass produced above the ground important in explaining aspect of yield and performance of the crop.

•Nitrogen Use Efficiency: Assesses the productivity of utilizing nitrogen fertilizer in grains.

5 DISCUSSION

This work examines the impacts of the integrated wheat-groundnut cropping system with reference to water use efficiency (WUE), carbon footprint, grain yield and grain nutritional profile sown in a rain-fed, semi-arid region. This study offers methods including the balanced fertilization, bio fertilization and mulching of the field some of the treatment seen to respond to the growing need for sustainable agriculture especially in areas scarce in water and nutrients. The following discussion section provides further evaluation of each analyzed parameter, comparison with other studies, and identification of the research's contribution in filling the gaps as well as the recommended improvements for the subsequent research.

Another of the leading goals of this study was therefore to enhance the WUE, given the common water limitation in rainfed areas. These results signal that the application of the treatments with integrated nutrient management (T8) and mulching (T7) led to a higher WUE as compared to the control treatment (T1). In particular, T8 provided the highest WUE, 3.6 kg/ha-mm, and T7 appeared to receive enhancement of 3.4 kg/ha-mm. It has been widely claimed by the erstwhile studies that integrated nutrient management and conservation techniques, like mulching, can canter the process of WUE since, through lesser evaporation at the surface and water conservation within root zone. This study affirms and extends these observations, and shows that these practices work in the context of a wheat-groundnut rotation crop in semi-arid environments where water management is crucial. Opportunities for improving WUE have been highlighted in this study to bear a ways to sustainable water management in similar Agricultural environments as this study targeting wheat-groundnut rotations for which previous researches have lacked effective application of these factors [13]. Equally important was the assessment of carbon footprint of various treatments in this study. An emission of 950 kg CO_2 eq/ha and 900 kg CO_2 eq/ha treatment have obtained with treatments that include biofertilizers (T6) and optimal NPK for wheat only (T2), while integrated treatments like T8 showed higher carbon footprint 1250 kg CO_2 eq/ha. Biofertilizers can partly replace synthetic fertilizers and, as such, contribute to reducing emissions [14]. Their interest stems from their environmental friendliness. Further, integrated treatments might raise emissions attributable to the increase in fertilisers and soil conditioners but at the same time create robust soil health and yield enhancement [15]. The fact that increasing yields has a cost to the environment brings to light the challenges that come with the balancing of nutrients for production to optimally occur. Therefore, this analysis adds to the knowledge of how some nutrient applications and biofertilizers affect greenhouse gas emissions, which other research has sometimes failed to explore while assessing wheat-groundnut systems [16].

Yield analysis indicated that there was maximum grain and pod yield in merged NPK for both crops (T4) and integration of nutrient management (T8). T8 produced the highest yield of the two crops; with wheat yielding 4100 kg/ha and the groundnut planting yielding 3500 kg/ha; therefore when all the fertility amendments are made available this produces the highest productivity. Similar conclusions can be drawn on the bases of two-site study of [17] which also supported the balanced fertilization regarding the effectiveness on the quantity and quality of the crops in the rainfed sites. This study helps a void missing in the previous studies conducted on this cropping system by comparing yield outcomes of individual components in the wheat-groundnut growing system under Nutrient Management Adviser strategies for nutrients in semi-arid regions [18].

In the biomass analysis, integrated treatments more favours because T8 had higher biomass 10,500 kg/ha suggesting enhancement in plant health and nutrient cycling in the soil. Thus, recommendation of balanced nutrient applications and proving that specific interventions can lead to high yield under adverse conditions [19]. Living up to the soil status plays huge significance in the rain-fed agricultural fields where nutrient depletion is most predominant. From the findings of the study it was seen that treatments mulching (T7) and integrated nutrient management (T8) enhanced the SOC of the treatment soils up to 1.20 % in T8. In addition, Mulching play a role in contributing to the pool of organic carbon by reducing soil erosion and stimulating the microbial decomposers [20]. Since improving SOM is a big hurdle especially in semi-arid regions, these practices provide an optimal way of improving on the situation. This study focuses on wheat and groundnut cropping systems and show that these crops gained from interventions in the health and fertility of the soil unlike other studies that view soil health in large cropping systems. The findings, orientated towards effective organic carbon accumulation, would fill gaps in the understanding of appropriate conservation management practices for wheat-groundnut systems [21].

Nutritional quality is one important measure of a cropping system performance for food crops like wheat and protein crops like groundnut. An overall closely integrated and balanced nutrient supply in the treatments T4 and T8 resulted into these higher protein contents in both crops. For instance, T8 was having the highest protein content in wheat which is 14.5% and groundnut which is 16.3% and the results showed that balanced nutrient management is having good impact on the quality of crops. Such results are in keeping with the study by [22] stating that optimum nutrient levels promote crop protein accumulation. This paper, by concentrating on yield, as well as the nutritional value of the crops that grow in the semi-arid zones, underscores the fact that shortage of quantity and quality complement one another: an aspect that several previous studies have not adequately captured in the yield of the wheat-groundnut systems. This focus on nutritional content makes the study particularly useful for areas where food security and content are linked, 11. Proper management of nitrogen is vital in reducing the impact of efficiency on the environment to the highest levels of productivity [23]. Stress treatments T1 and

T8 had high nitrogen use efficiency with T8 having the highest value of NUE of 16.8 grain/kg N. These ideas support the existing research of [24] that named integrated nutrient management beneficial for nitrogen uptake, and negative for the environment. sustainable agriculture practices are highlighted in this study while making a provision for a plausible NUE enhancement framework in W-G systems referred to by (Suryakumar et al., 2024). Hence this study fills a gap in research done on NUE focused practices within rainfed, nutrient-limited systems and provides understanding on how to enhance sustainable use of nutrient additives.

5.1 Recommendations

In view of these, the following recommendations are made for enhancing the sustainability and productivity of wheat–groundnut in the semi-arid regions. First, using IM system of nutrient management that uttermost use of chemical fertiliser, bio-fertilisers and mulch is suggested to entertain high WUE, yield and soil condition. Second, biofertilizers should be used in place of some synthetic nitrogen sources with the intention of halving the carbon footprint and still get good yields. Third, for conserving of soil through mulching, it is encouraged because promotes organic carbon of the soil and WUE by increasing the water that could be absorbed by the soil by the activity of microorganisms.

Moreover, it is time to sustain the investigation of the adaptative cropping systems given the climate volatility. Some future studies should focus on effects of these practices on the soil health and productivity in the long run as well as cross climatic regions so as to get a wide applicability. Furthermore, there is the need for expansion and adoption of advances tools, input and technology like precision agriculture technology for improved management of inputs in the enhance sustainability of the wheat-groundnut system. Therefore, this study helps to fill existing gaps in the literature regarding sustainable and effective agricultural practices by providing a comprehensive insight into effective nutrient and water management techniques that would improve WUE, decrease CO_2 emissions, and promote yield and nutritional quality of crops under rainfed environment on a wheat-groundnut cropping system. In the context of wicked science for wicked challenges, this work presents a number of possible practical solutions for improving WUE, carbon footprint, and soil health in wheat-groundnut rotations in semi-arid production zones, and supporting food production alongside ecosystem sustainability.

6 CONCLUSION

This research effectively achieves the objectives of raising water productivity and reducing the carbon footprint in the wheat groundnut cropping system under rainfed environments with better nutritional quality. The work entails the analysis of multiple agronomic factors including early maturity varieties, optimum nutrient use and intensity and methods of conservation of the soil; this makes the study informative to crop productivity and sustainability in the regions that are substantially arid. The study proves that utilization of integrated nutrient management supplemented with bio fertilizer and modified soil conservation measures enhance water use efficiency, yield and health of the soil without disturbing the ecological balance. Therefore, the study advances scientific literature on an important aspect of interventions relating to the improvement of resource utilization and the management of climate adversities in agricultural production. In addition, the study includes suggestions for improving yields in wheat-groundnut rotations based on research findings, these findings may prove useful to future generations of agriculture in rainfed regions, enhancing food security and economic sustainability in regions endowed with scarce water resources.

COMPETINGINTERESTS

The authors have no relevant financial or non-financial interests to disclose.

AUTHOR CONTRIBUTIONS

Alvina Faraz, Mukhtar Ahmad; Conducted the main experiment and measured the growth parameters and wrote the original draft: Alvina Faraz, Mukhtar Ahmad, Nadir Ali and Mansoor Ali; Made the major contributions to conducting experiments, drafting of the manuscript: Alvina Faraz, Mukhtar Ahmad, Nadir Ali, Mansoor Ali Muhammad Asim, Mansoor Ali, Usama Ashiq ,Saif Ullah: Analyzed the data Alvina Faraz, Mukhtar Ahmad, Nadir Ali and Mansoor Ali i; Reviewed, edited and prepared the MS for sub- mission: Alvina Faraz, Mukhtar Ahmad, Nadir Ali, Abdul Rehman.

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