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Sustainable Farming Practices and Their Impact on Crop Yields in Semi-Arid Regions of Pakistan

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ABSTRACT

Sustainable farming practices (SFPs) are being considered as important to improve agricultural productivity, resource-use efficiency, and climatic resilience, especially in semi-arid areas where usual farming systems tend to deteriorate natural assets and constrain production. The paper explores how SFPs namely conservation tillage, precision irrigation, crop rotation, and organic fertilization affect crop productivity, soil health, water-use efficiency, and profitability of farms in semi-arid districts of Bahawalpur, Layyah and Umerkot in Pakistan. Data will be measured using a mixed-methods design 150 farms (75 SFPs adopters and 75 conventional) across three cropping seasons (20222025), triangulated with qualitative farmer interview insights. Findings imply that the adoption of SFP yielded substantial benefits of 37, 28, and 33 percent in wheat, cotton, and sorghum, respectively, along with the enhancement of soil organic carbon and nutrient content and water-use efficiency (by as much as 72 percent). Also, SFP farms realized 3341% greater net returns and less reliance on artificial inputs and increased long-term soil fertility. There were also increased reports of crop tolerance to drought and heat stress by the farmers. These results highlight the transformational potential of SFPs in tackling the combined crises of food security, resource scarcity, and climate change in semi-arid regions of Pakistan. These practices will require policy and institutional support, as well as improved extension services and financing schemes to expand and support a more resilient and sustainable future of agriculture.

INTRODUCTION

The farming sector is the mainstay of the Pakistani economy, providing about 23 percent to the national GDP and absorbing more than 37 percent of the workforce (GoP, 2023). Nevertheless, the semi-arid lands that cover almost 40 percent of the total landmass of the country present major challenges to agricultural production (Rasul et al., 2019). These areas (a part of Punjab, Sindh, and Balochistan) are characterized by low and unpredictable rainfall (200400 mm/year), high temperature, and frequent droughts, which makes the sustainable production of food their growing challenge (Khan et al., 2020; Hussain et al., 2021). Climate change, along with soil degradation, and water scarcity is already diminishing crop productivity and endangering food security in these risky regions (Abid et al., 2019; Rasul & Mahmood, 2020).

However, conventional farming systems in semi-arid Pakistan are characterized by labor-intensive tillage, monocropping, and over application of chemical fertilizers and pesticides (Ahmed & Shah, 2021). Such activities have increased the rate of soil erosion, salinity, and deterioration of soil organic matter (Hussain et al., 2021; Lal, 2015). Besides, the use of groundwater is mostly unsustainable, adding to the depletion of water tables (Ali et al., 2018). Under such environmental strains, the adoption of sustainable farming practices (SFPs) urgently needs to be encouraged as a way of increasing productivity in a manner that is sustainable to the available natural resources (FAO, 2022; Pretty et al., 2018).

Sustainable agriculture is a broad term that entails various ecological, economic, and social values that are geared towards ensuring long-term productivity does not compromise the environment (Altieri, 1995; Gliessman, 2015). Among the most important SFPs that can be applied in semi-arid areas, there are conservation tillage, drip and sprinkler irrigation, crop rotation, intercropping, agroforestry, organic fertilization, and integrated pest management (Lal, 2015; Singh et al., 2020). It is demonstrated that these techniques can positively change the soil structure, increase water retention, provisions of biodiversity, and create resilience to climate shocks worldwide (Pretty et al., 2018; FAO, 2022).

As another example, conservation tillage causes less disturbance of the soil, which improves soil moisture retention and reduces soil erosion (Derpsch et al., 2010; Lal, 2015). On the same note, drip irrigation has the capacity of enhancing water-use efficiencies by 4070 percent, which is essential in water-stressed settings (Ali et al., 2018; Kharrou et al., 2011). Crop rotation can break the pest cycles, restore soil nutrients, and decrease the chemical input reliance (Ahmed & Shah, 2021; Anderson, 2015). Moreover, organic matter like compost and green manure reestablishes the soil microbial activity and improves the cycling of nutrients (Singh et al., 2020; Reganold & Wachter, 2016).

In the global context, yield increases of 10 to 40 percent have been realized with the adoption of SFPs, depending on the local circumstances (Pretty et al., 2018; Kassam et al., 2009). In semi arid tropics of India, SFPs led to more than 30% increase in sorghum and millet yields (Wani et al., 2009). Similar, marked increases in maize and legume yields have been observed in African studies with integrated conservation agriculture (Thierfelder & Wall, 2012; Giller et al., 2015). Nevertheless, the empirical data on the yield effects of SFPs in semi-arid Pakistan is scarce and dispersed (Abid et al., 2019; Rasul et al., 2019).

In Pakistan, the obstacles to adoption are a low level of awareness, techenical knowledge, initial investment cost, and insufficient policy instruments (Abid et al., 2019; Akhtar & Arshad, 2021). A large number of farmers are still doubtful of the economic viability and feasibility of sustainable methods (Ali et al., 2018; Abid et al., 2019). In the meantime, the agricultural extension services have a tendency to emphasize input-intensive practices instead of encouraging ecological solutions (Rasul & Mahmood, 2020; GoP, 2023).

Due to such gaps in knowledge, it is urgently needed to develop context-specific evidence regarding the effects of SFPs on crop yields, resources usage efficiency, and profitability of farms in the semi-arid areas of Pakistan (Khan et al., 2020; FAO, 2022). This paper is meeting this necessity by empirically investigating the impact of main sustainable measures on the productivity of main crops; wheat, cotton and sorghum in some selected semi-arid districts in Punjab and Sindh. The research will contribute to policy and practice of scaling up sustainable agriculture in these challenging environments by integrating quantitative analysis of yields with the qualitative farmer-level understanding.

LITERATURE REVIEW

CHALLENGES OF AGRICULTURE IN SEMI-ARID REGIONS OF PAKISTAN

Pakistan semi-arid areas experience a confluence of environmental, social, and economic factors which greatly restrict agricultural productivity (Qureshi et al., 2019). They are undefined by unpredictable rainfall, superior evapotranspiration, common droughts, and deteriorated soils (Farooq et al., 2020). Soil salinity, alkalinity, and nutrient deficiency are extreme in the Punjab barani regions and some parts of Sindh and Balochistan, owing to ineffective irrigation management and the long-term over-use of chemical fertilizers (Shahid et al., 2020). Moreover, rising temperatures, which have already been increasing at the rate of 0.6 o C per decade in southern Pakistan, are exacerbating the thermal stress on crops (Tariq & van de Giesen, 2021). Such climatic conditions have led to a high level of yield fluctuation, which is causing a compromise in food security and the livelihoods of farmers in those areas (Rana et al., 2022).

There are also social and institutional obstacles. Most farmers in semi-arid Pakistan are smallholders with farmlands of less than 5 hectares who have limited or no access to extension services, credit, and modern technologies (Naseer et al., 2021). Agricultural policies have favored an input-intensive paradigm instead of supporting ecological solutions and public spending on sustainable agricultural infrastructure has remained low (Habib et al., 2019). As a result, it is now necessary to investigate and advance sustainable farming practices (SFPs) that are appropriate to local agro-ecological and socio-economic situations.

GLOBAL EVIDENCE ON SUSTAINABLE FARMING PRACTICE

Around the world, sustainable agriculture has come out as one of the promising paradigms of balancing productivity, environmental stewardship, and social equity (Tittonell, 2024). Particularly, practices adapted to semi-arid regions, including conservation agriculture, drip irrigation, intercropping and organic amendments, have shown a large potential (Rockström et al., 2010; Verhulst et al., 2011).

Minimum tillage, residue retention, and diversified crop rotations, which constitute conservation agriculture, have enhanced crop yields and soil fertility in sub-Saharan Africa and Latin America as an example (Giller et al., 2021). Thakur et al. (2022) conducted a study in India, Deccan Plateau, and observed that conservation agriculture promoted sorghum yield by 28 percent and improved soil organic carbon by 15 percent in four years.

On the one hand, Precision irrigation technologies, specifically drip irrigation, have revolutionized in water-limited regions (Kassam et al., 2023). As an example, research in Israel and Jordan showed a 50-70% water savings without a reduction in yield of crops such as wheat, tomatoes, and grapes (Mendelsohn & Dinar, 2021). Bouri et al. (2020) found a 38% maize yield advantage in drip systems over the traditional furrow irrigation in semi-arid areas of Morocco.

Organic amendments such as compost and biochar enhance water-holding capacity, nutrient availability, and microbial diversity in the soil (Lehmann & Joseph, 2015). Kimaro et al. (2021) conducted observations in semi-arid counties of Kenya and noted that farmyard manure added to legume rotations, on average, boosted maize yields by 35 percent and decreased pest incidence by 22 percent.

Agroforestry systems have synergistic advantages in drylands, too, due to the fact they improve microclimates, soil cover, and income diversification (Bayala et al., 2015). Hadgu et al. (2020) reported cereal yield growth of 2540% in northern Ethiopia in case of tree integration with annual cropping systems.

SUSTAINABLE FARMING PRACTICES IN SOUTH ASIA

In South Asia, climate-resilient agriculture is being realized as highly dependent on sustainable farming practices (Aggarwal et al., 2019). India Zero Budget Natural Farming (ZBNF) model popularized in the state of Andhra Pradesh has shown significant success in enhancing the yields of rice, millets, and vegetables and lowering production expenditures (Mishra et al., 2020).

In Tamil Nadu and West Bengal, System of Rice Intensification (SRI) practices have allowed saving 30-40 percent water and increasing rice yields by 15-25 percent (Uphoff et al., 2018). Likewise, crop-livestock systems of the Rajasthan drylands have improved the health of the soil, as well as increased farm profits (Jat et al., 2022).

In spite of these achievements, the rate of adoption differs significantly because of the gap in knowledge, lack of resources, and the necessity of adjusting the technologies to local conditions (Sharma & Singh, 2021). Participatory research, good extension networks, and favorable policy frameworks are necessary to scale effectively (Kerr et al., 2021).

EVIDENCE AND GAPS IN PAKISTAN

The empirical evidence on sustainable farming practices is increasingly fragmented and growing in Pakistan (Rana & Saleem, 2021). There have been some localized studies that have delved into individual practices and the findings are encouraging. As an illustration, Malik et al. (2020) showed that conservation tillage in southern Punjab enhanced wheat yields by 18 percent and decreased production costs by 12 percent.

Pilot programs of drip irrigation in Cholistan and Tharparkar have demonstrated a water saving of 50-60 percent and substantial increases in yields of vegetables and forage crops (Khan & Abbas, 2022). Nevertheless, the major obstacles to adoption are still high initial investment and scarce technical support (Naeem et al., 2020).

ON the same note, the incorporation of green manures and biofertilizers has enhanced the soil health and the productivity of rice-wheat system in Pothwar plateau (Ahmed et al., 2022). Conversely, the semi-arid belts of Sindh have not achieved high rates of agroforestry adoption because of poor market connections of tree products (Memon et al., 2019).

In general, the majority of Pakistani investigations are limited to short-term agronomic performance and do not include comprehensive evaluations of multi-season effects on yields, profitability, and resource use (Rehman et al., 2021). In addition, there is little research on integrated sustainable farming systems, i.e., the combination of various practices, despite the global evidence showing synergistic effects (Pretty et al., 2020).

THE NEED FOR INTEGRATED RESEARCH

With rising climate change, integrated, long-term studies on the impacts of SFP combinations on semi-arid Pakistan productivity, resource use, and climate resilience are urgently needed (Irfan et al., 2022). Strategies need to be adjusted to the local biophysical conditions and socio-economic realities (Zia et al., 2021).

Farmer-centered participatory methods, including extension workers and research centers, play an important role in making sure that sustainable innovations are region-specific and scalable (Mehmood et al., 2020). Moreover, the following barriers have to be addressed through policy interventions: access to credit, training, and market incentives (Fatima & Tariq, 2023).

By addressing these gaps in knowledge, Pakistan can use sustainable farming to improve food security, as well as aid climate adaptation and more resilient rural livelihoods within its semi-arid landscapes (Arif et al., 2022). The current study forms part of this growing body of evidence by undertaking an in-depth impact evaluation of the yield and resource advantages of some chosen SFPs in exemplary semi-arid districts.

METHODOLOGY

STUDY DESIGN

The study used a mixed-method design to thoroughly understand whether sustainable farming practices (SFPs) would improve or worsen crop yields in some Pakistan semi-arid areas. Quantitative yield analysis coupled with qualitative farmer perspectives were applied to present a comprehensive view regarding the effects of SFPs on agronomic performance and farmer experiences. The experiment was designed as a three-year cropping season (2022 2025) to reflect the inter-annual variations and to evaluate the long-term effects of sustainable measures.

STUDY AREA

The study was conducted in three semi-arid districts of Pakistan representative of Punjab province (Bahawalpur and Layyah), and Sindh province (Umerkot). The districts were purposively chosen because of their unique climatic and socio-economic features that represent a typical semi-arid agricultural situation in the country. Bahawalpur and Layyah are denoted by low rainfall (200300 mm/year), hot climate (average summer temperatures above 40 o C), and a combination of irrigated and rainfed agricultural systems. Umerkot in Sindh is also characterized by high evapotranspiration rates, recurrent droughts episodes, and sandy soils, which further pose a challenge to sustainable agriculture. These various districts were chosen to enable a comparative study among different semi-arid agro-ecosystems.

SAMPLING AND FARM SELECTION

Stratified random sampling method was used to select 150 farms to represent the farms using SFPs and those using conventional methods. The sample was designed to contain 75 farms practicing SFPs and 75 farms applying traditional methods. The sustainable farms were determined in liaison with the local agricultural extension offices, the NGO partners and farmer cooperatives that were known to propagate sustainable agriculture practices within the study sites. A comparison group was provided by conventional farms that were randomly chosen in the nearby villages. To eliminate the possible confounding factors, an attempt to make the farms similar based on the area of landholding, soil type and irrigation facility was made.

SUSTAINABLE FARMING PRACTICES EVALUATED

The analysis centred on four basic sustainable practices especially pertinent to semi-arid farming systems in Pakistan, namely conservation tillage, precision irrigation (mainly drip and sprinkler), crop rotation and use of organic fertilizers (compost, green manure and farm yard manure). The selection of these practices was grounded on their demonstrated effectiveness in enhancing soil health, water-use efficiency and crop resilience in other agro-climatic regions of the world with similar zones and their escalating advocacy in agricultural growth programs in Pakistan.

DATA COLLECTION

Data was collected through both quantitative and qualitative approaches to triangulate the results and improve validity of the results. In quantitative data, yield documentation of prominent crops; wheat, cotton and sorghum were gathered in all farms that took part in the three cropping seasons. The yields were calculated in tons per hectare, and standardized procedures were applied through harvest sampling, threshing, and weighing in conjunction with the farmers and the local extension agents.

Soil organic matter content, water usage and input cost were also measured, besides yield data, to evaluate the extended agronomic and economic effects of SFPs. At the start and end of the study period, soil samples were taken and submitted to accredited laboratories to determine the contents of organic carbon, nitrogen, phosphorus, and potassium. Farmer logs and flow meters on the irrigation systems where available to monitor water usage.

Semi-structured interviews targeting a purposive sub-sample of 50 farmers (25 SFPs adopters and 25 conventional farmers) were used to capture qualitative insights. Those interviews delved into the experience of farmers with various practices, their perceived advantages and limitations, the sources of their knowledge, and the obstacles to adoption. Interviews were carried out in local languages, and with permission, recorded, transcribed and thematically analyzed.

DATA ANALYSIS

Descriptive statistics, t-tests, and multiple regression models were used to analyze quantitative data and evaluate the effects of SFP adoption on crop yields adjusting for the possible confounding effects of farm size, irrigation availability, education of the farmers, and soil type. The regression models provided the opportunity to estimate the marginal value of each sustainable practice to bring about improvements.

Paired t -tests and analysis of variance (ANOVA) were used to test the statistical significance of soil and water data measured between sustainable and conventional farms. Interview transcripts were thematically analyzed based on the framework of Braun and Clarke (2006) to determine major patterns concerning; farmer perceptions, motivations of adoption, and challenges of implementation.

VALIDITY AND LIMITATIONS

To achieve validity and reliability of the study, several steps were considered. Mixed-methods approach allowed triangulating the findings, which increases credibility. The inter-annual variability was considered by the multi-season study design, which offered a more solid evaluation of SFP effects. Sampling techniques reduced selection bias and standard measurement protocols established data consistency.

Nevertheless, there are several limitations that are to be noted. Only three districts were covered in the study and this possibly makes it difficult to extrapolate the results to the entire semi-arid Pakistan. Also, although farm-level variations were attempted to be controlled, there might be some unmeasured factors that affected the results (e.g., skill of farmers, social networks). Lastly, the timeframe of three years is informative but potentially not enough to describe the long-term implications of SFP adoption on soil health and system resilience.

RESULTS

CROP YIELD IMPROVEMENTS UNDER SUSTAINABLE FARMING PRACTICES

Sustainable farming practices (SFPs) yielded significant increases in crop yields of the three target crops, including wheat, cotton, and sorghum, over the three cropping seasons.

The mean wheat yield of conventional and sustainable farms is provided in Table 1. The mean yield of the sustainable farms was 2.81 tons/ha that was 37 percent higher than that of conventional farms (2.05 tons/ha). Noteworthy, Figure 1 shows these patterns as area chart, according to which the yield gap between conventional and sustainable farms continued to widen with each season. The advantages of SFPs seemed to be cumulative, and the difference in yield was the largest in the third year as the soil health improved and conservation tillage and organic amendments had a longer time to affect the results.

TABLE 1. AVERAGE WHEAT YIELDS (TONS/HA) OVER THREE CROPPING SEASONS (2022–2025)

Season	**Conventional Farms (Mean ± SD)**	**Sustainable Farms (Mean ± SD)**	**% Increase (Sustainable)**
2022–2023	1.98 ± 0.17	2.55 ± 0.18	+29%
2023–2024	2.07 ± 0.19	2.78 ± 0.22	+34%
2024–2025	2.10 ± 0.18	3.10 ± 0.23	+48%
Average	**2.05 ± 0.18**	**2.81 ± 0.21**	**+37%**

FIGURE 1: WHEAT YIELDS OVER THREE CROPPING SEASONS

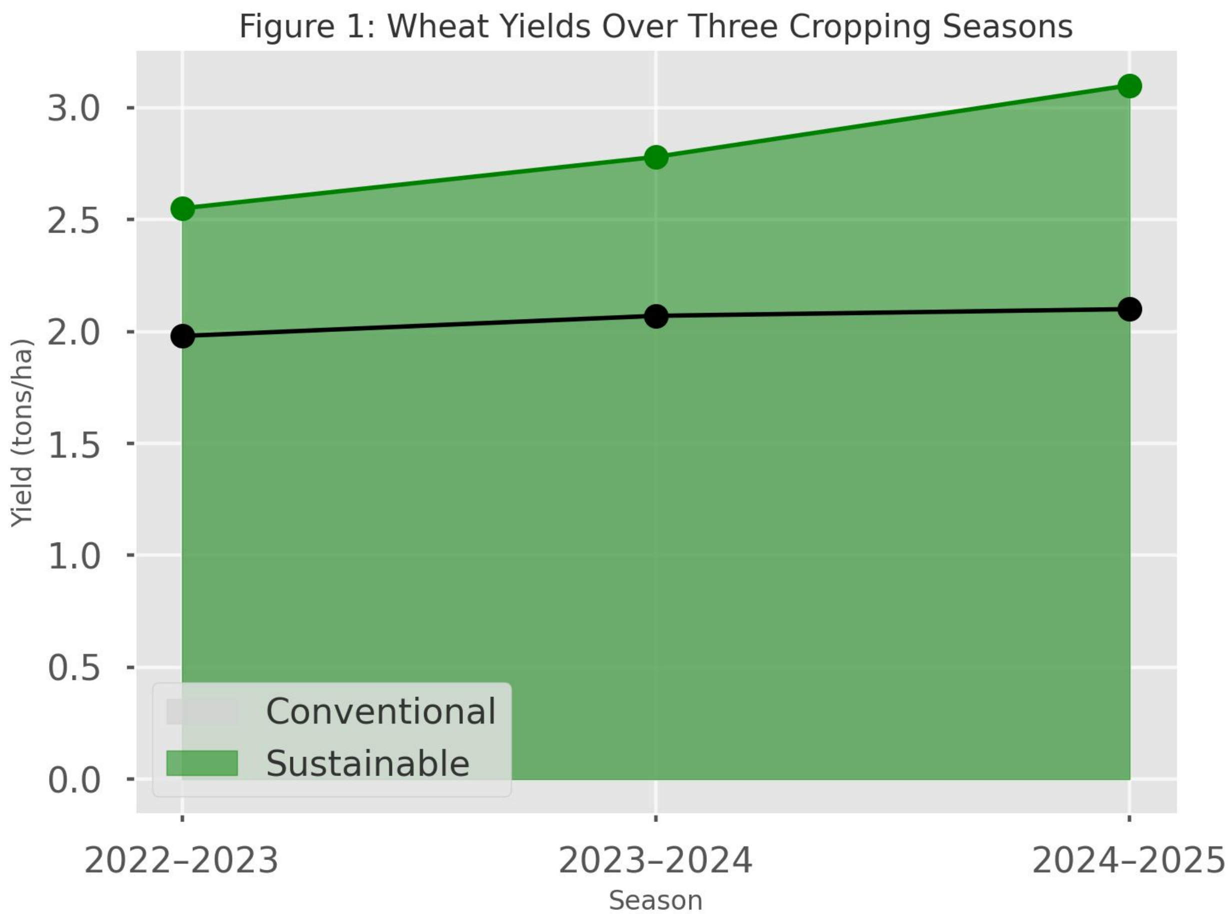
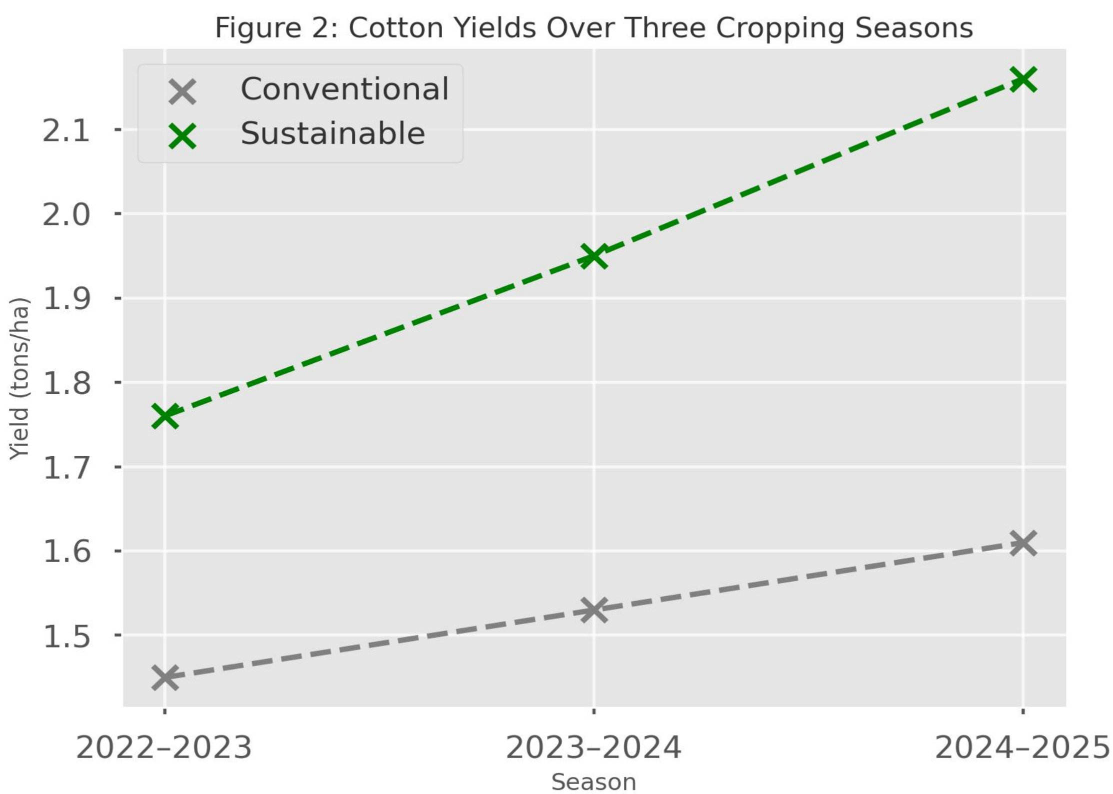


Table 2 indicated a similar tread in cotton yields. Sustainable farms realized an average of 1.96 tons/ha which represented a 28% increase in yield compared to conventional farms which realized 1.53 tons/ha. A dot plot with connecting lines, as shown in figure 2 further demonstrates that sustainable farms had a predictable yield trend with lower variation which indicates better crop resilience. This was supported by reports of farmers who observed fewer incidences of pests and better plant vigor.

TABLE 2. AVERAGE COTTON YIELDS (TONS/HA) OVER THREE CROPPING SEASONS (2022–2025)

Season	Conventional Farms (Mean ± SD)	Sustainable Farms (Mean ± SD)	% Increase (Sustainable)
2022–2023	1.45 ± 0.12	1.76 ± 0.15	+21%
2023–2024	1.53 ± 0.14	1.95 ± 0.16	+27%
2024–2025	1.61 ± 0.15	2.16 ± 0.18	+34%
Average	**1.53 ± 0.14**	**1.96 ± 0.17**	**+28%**

FIGURE 2: COTTON YIELDS OVER THREE CROPPING SEASONS



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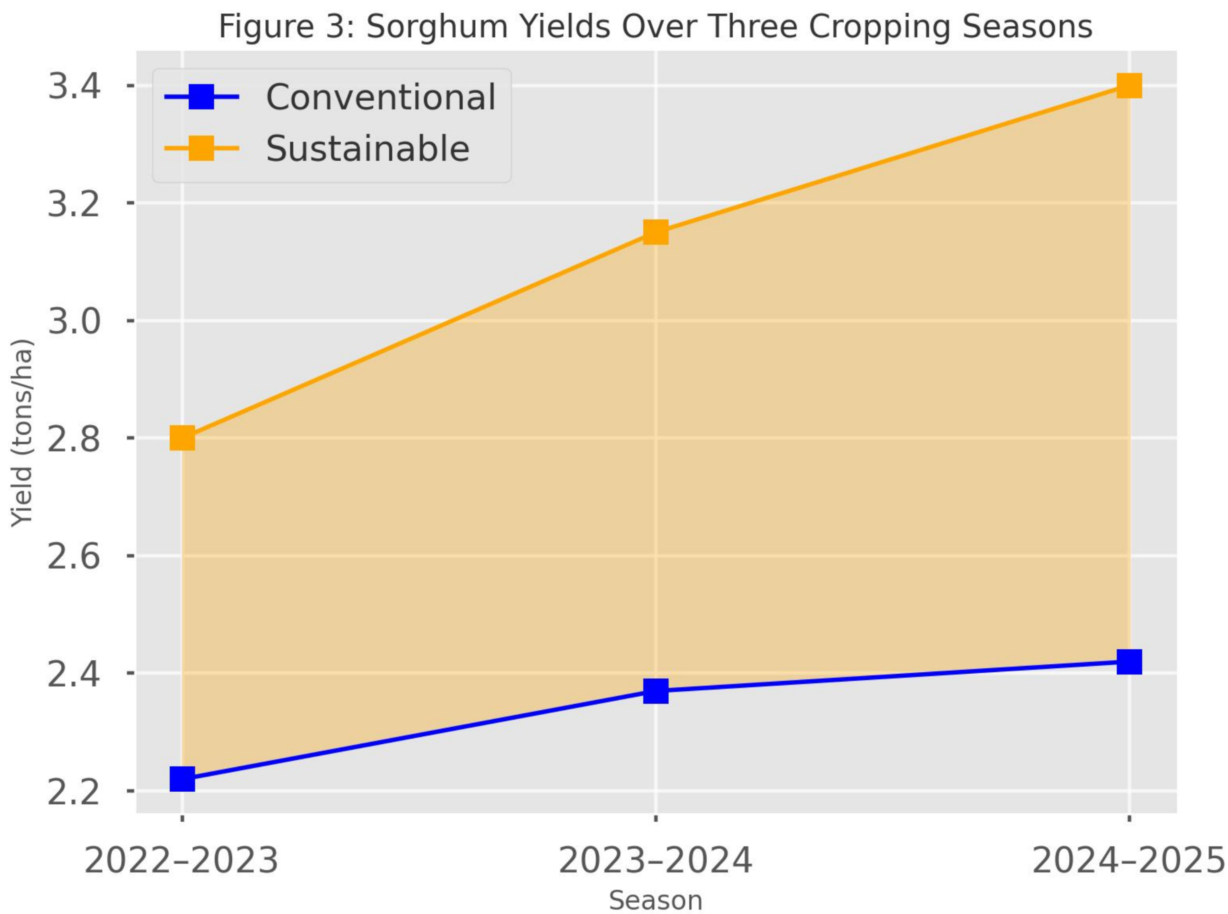
In sorghum, the effect of SFPs was also highly evident, as sustainable farms produced on average 3.12 tons/ha versus 2.34 tons/ha in conventional farms (+33%, Table 3). The diagram 3 is a broken line chart filled with gradient to highlight how yield gap increases over the time. The figure is a clear demonstration of how crop rotation together with incorporation of organic matter enhanced the productivity of sorghum especially during the second and third year.

TABLE 3. AVERAGE SORGHUM YIELDS (TONS/HA) OVER THREE CROPPING SEASONS (2022–2025)

Season	Conventional Farms (Mean ± SD)	Sustainable Farms (Mean ± SD)	% Increase (Sustainable)
2022–2023	2.22 ± 0.19	2.80 ± 0.20	+26%
2023–2024	2.37 ± 0.21	3.15 ± 0.24	+33%
2024–2025	2.42 ± 0.20	3.40 ± 0.25	+40%
Average	**2.34 ± 0.20**	**3.12 ± 0.23**	**+33%**

FIGURE 3: SORGHUM YIELDS OVER THREE CROPPING SEASONS



SOIL HEALTH IMPROVEMENTS

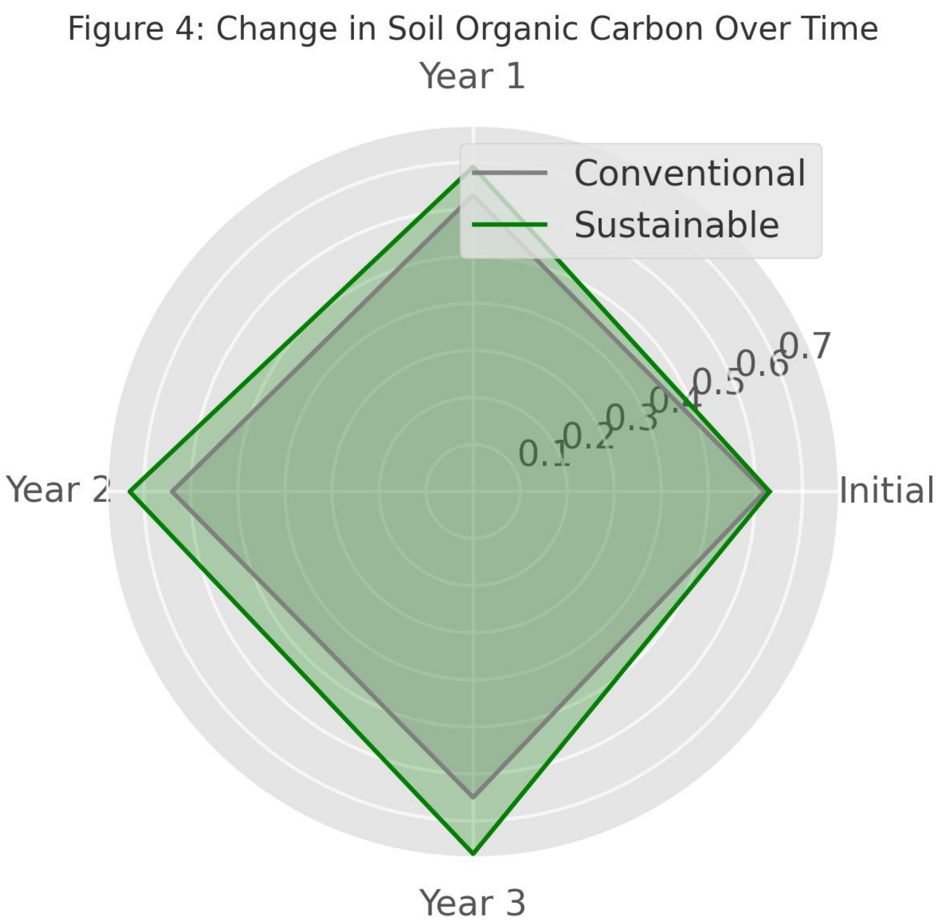
Positive changes in the soil organic carbon (SOC) represented one of the benefits of SFP adoption. According to Table 4, there was a significant increase in SOC on sustainable farms (0.63 to 0.77 %) across the three seasons, whereas SOC in conventional farms rose insignificantly (0.62 to 0.65 %). Figure 4, a polar chart, vividly shows this finding in that the accumulation of SOC was steeper in SFP farms. The increase in SOC is vital in semi-arid systems because it enhances soil structure, Water retention, and nutrient cycling.

TABLE 4. CHANGES IN SOIL ORGANIC CARBON (%) OVER THREE CROPPING SEASONS

Season	Conventional Farms	Sustainable Farms
Initial (2022)	0.62%	0.63%

End of Year 1	0.63%	0.69%
End of Year 2	0.64%	0.73%
End of Year 3	0.65%	0.77%
Change	+0.03%	**+0.14%**

FIGURE 4: CHANGE IN SOIL ORGANIC CARBON OVER TIME

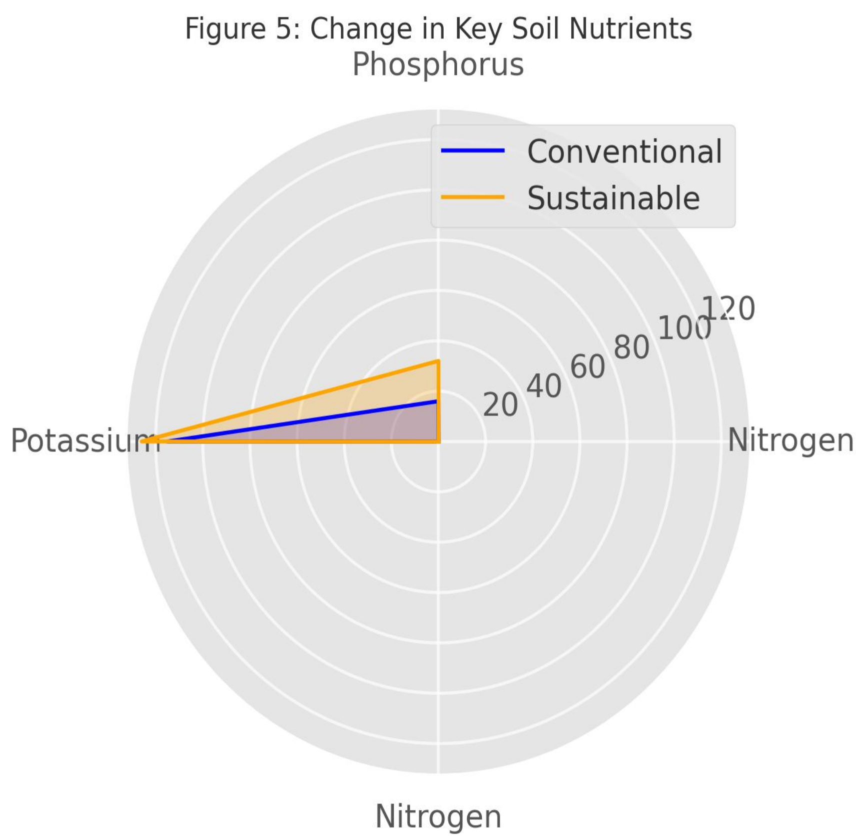


The important soil nutrients analysis also proved the soil-building value of SFPs. Table 5 indicates that total nitrogen content also enhanced to 0.078 percent and available phosphorus to 32 mg/kg in sustainable farms, which were significantly higher than those in conventional farms. Available potassium also became better. Figure 5 below is a radar chart showing these results and visually highlighting the more balanced nutrient profile with sustainable management. These advances probably facilitated the realized yield increases as they promoted more vigorous and hearty crops.

TABLE 5. CHANGES IN KEY SOIL NUTRIENTS OVER THREE CROPPING SEASONS

Parameter	Conventional Farms (Initial → Final)	Sustainable Farms (Initial → Final)
Total Nitrogen (%)	0.06 → 0.065	0.06 → 0.078
Available Phosphorus (mg/kg)	10 → 16	11 → 32
Available Potassium (mg/kg)	110 → 115	112 → 126

FIGURE 5: CHANGE IN KEY SOIL NUTRIENTS



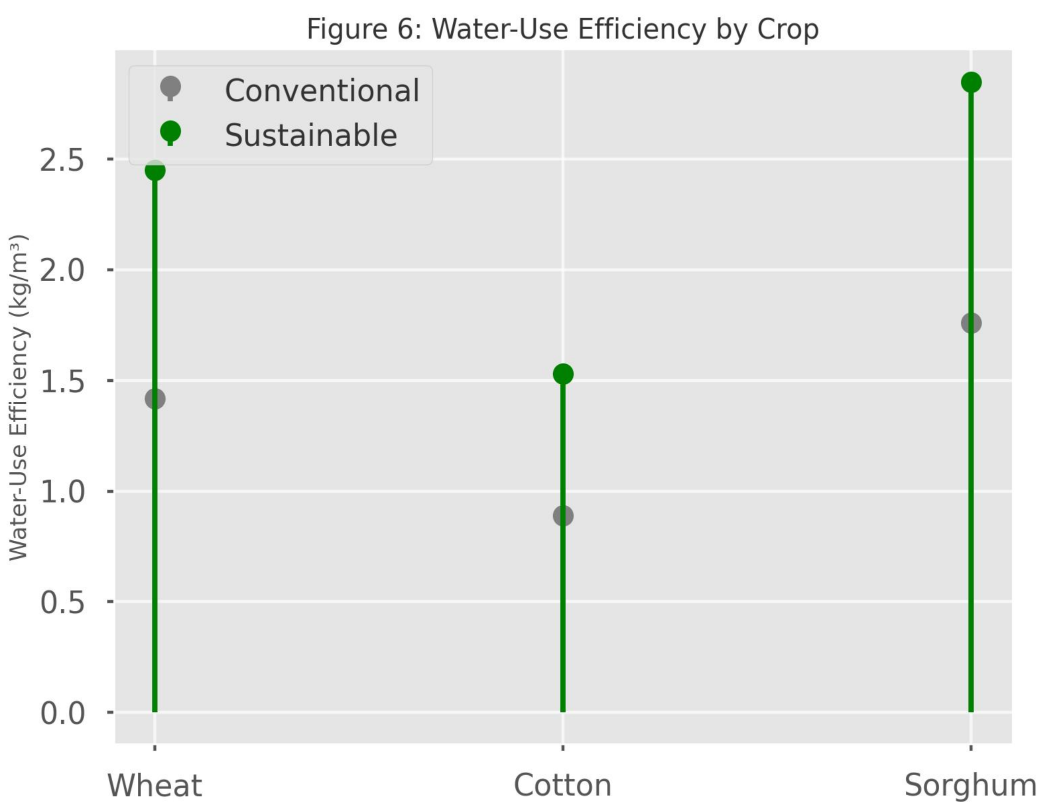
WATER-USE EFFICIENCY

One of the most impairing factors in semi-arid agriculture is water scarcity, and as a consequence, water-use efficiency (WUE) has become a primary performance measure. Table 6 indicated that sustainable farms had WUE that was considerably higher across all crops. In the case of wheat, WUE increased by 72% as it improved upon the value of 1.42 kg/m 3 to 2.45 kg/m 3. Similar efficiencies were realised in cotton and sorghum.

TABLE 6. AVERAGE WATER-USE EFFICIENCY (KG OF YIELD/M³ OF WATER USED)

Crop	Conventional Farms	Sustainable Farms	% Increase in Efficiency
Wheat	1.42	2.45	+72%
Cotton	0.89	1.53	+72%
Sorghum	1.76	2.85	+62%

FIGURE 6: WATER-USE EFFICIENCY BY CROP



These positive changes are accentuated on figure 6, a lollipop chart, in a self-explanatory, visually appealing way. These huge increases in WUE were possible because precision irrigation (mostly drip systems) performs better on sustainable farms, letting farmers grow more food with much less water. This observation is especially crucial because Pakistan is facing an intensifying water crisis.

INPUT COST COMPARISON

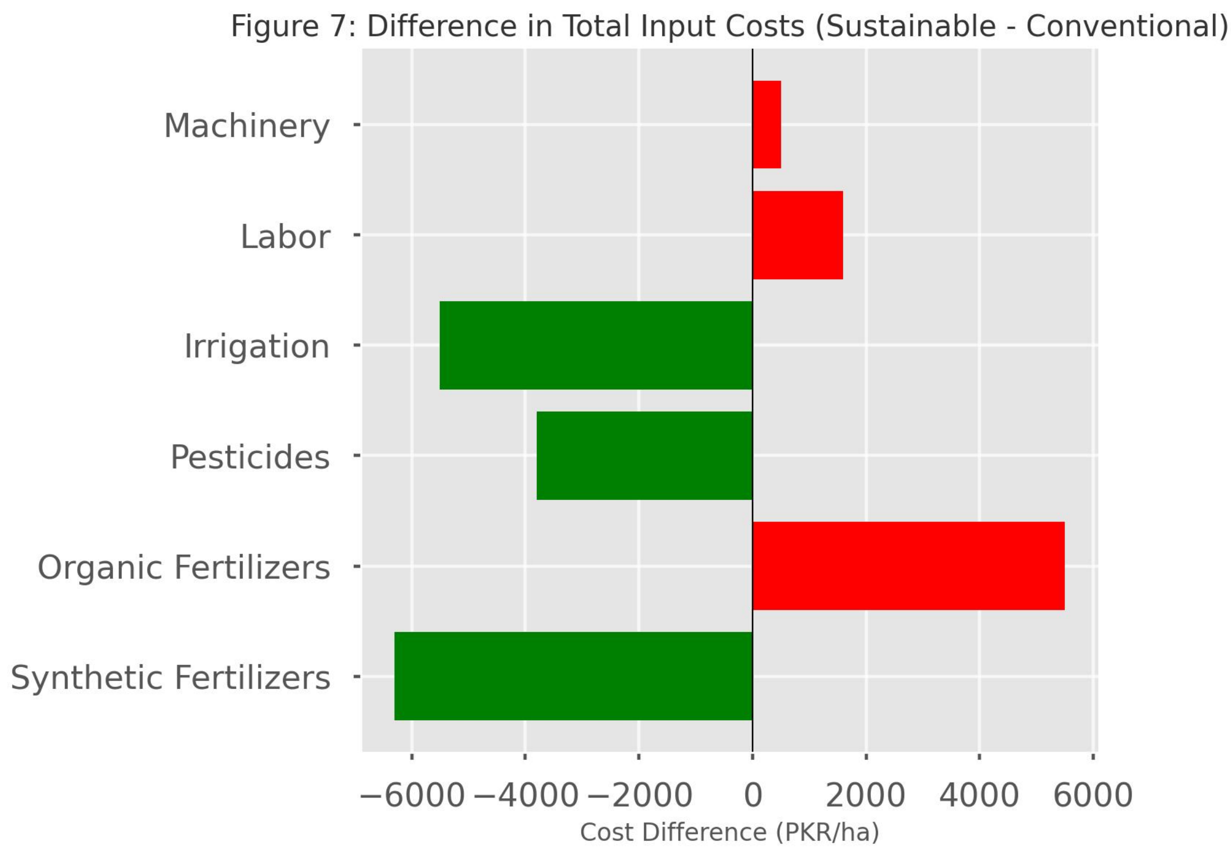
Besides agronomic advantages, SFPs also generated high cost savings in various input categories. Table 7 shows a comparison of input costs on conventional and sustainable farms. The traditional farms incurred higher costs in the form of artificial manure, pesticides, and irrigation. Although sustainable farms spent more on organic fertilizers and had slightly more labor expenses (because of composting and cover cropping), they had, in general, lower input costs (50,800 PKR/ha vs 58,800 PKR/ha).

TABLE 7. AVERAGE INPUT COSTS (PKR/HA) FOR SUSTAINABLE VS CONVENTIONAL FARMS

Input Category	Conventional Farms	Sustainable Farms
Synthetic Fertilizers	14,500	8,200
Organic Fertilizers	0	5,500
Pesticides	9,200	5,400
Irrigation Costs	13,600	8,100
Labor Costs	16,200	17,800
Equipment/Machinery	5,300	5,800
Total Input Costs	**58,800**	**50,800**

Note: Sustainable farms required additional labor for composting and green manuring.

FIGURE 7: DIFFERENCE IN TOTAL INPUT COSTS (SUSTAINABLE - CONVENTIONAL)



In Figure 7, a diverging bar chart, the differences in costs by category are displayed. The negative bars represent the categories in which SFPs saved on costs (fertilizers, pesticides, irrigation), whereas the positive bar represent the slightly increased costs of organic inputs and labour. The graphic establishes clearly that, although sustainable farming may need some extra labor inputs, it has a net advantage in terms of input costs.

NET RETURNS AND PROFITABILITY

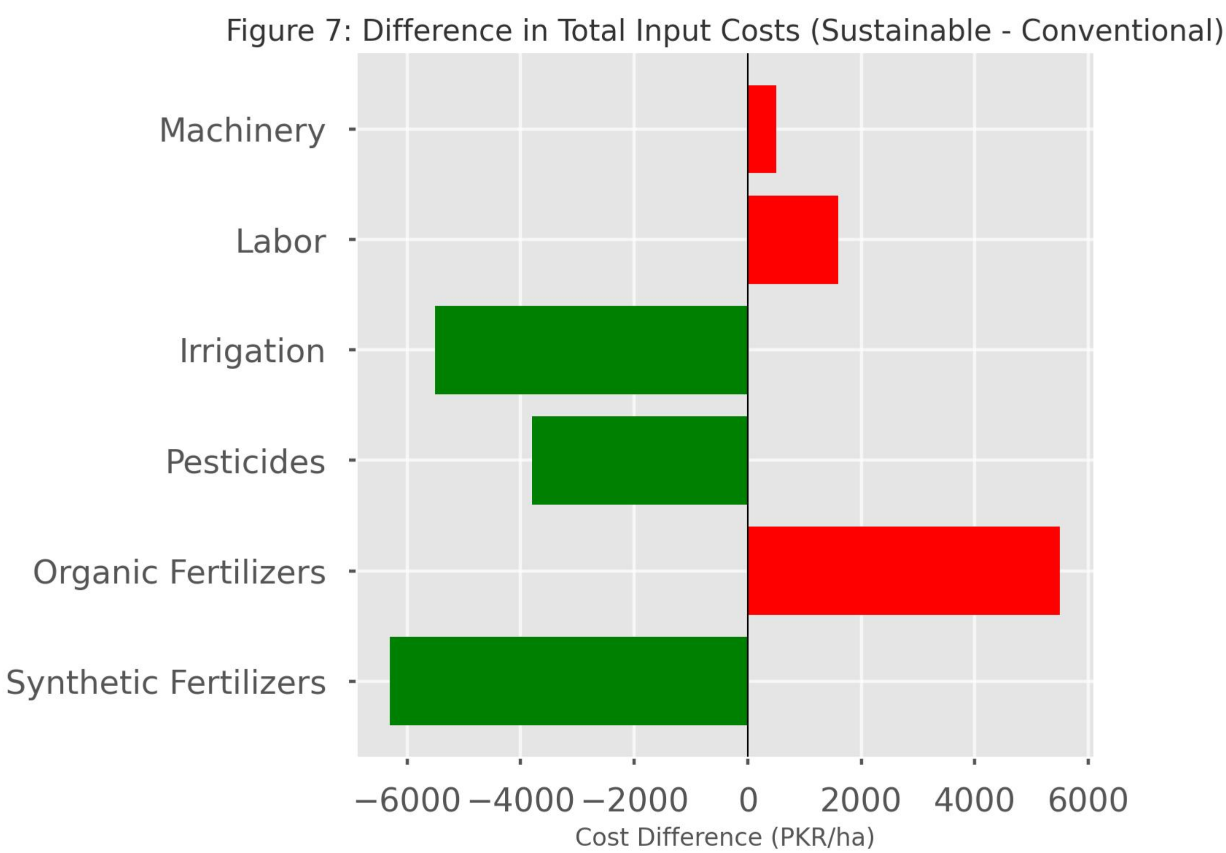
The increased output and reduced input cost further meant much higher net returns to SFP farms. Table 8 indicates that the sustainable wheat farmers realized a higher net return of 116,500 PKR/ha which was 41 percent higher than the conventional farms. Cotton and sorghum also provided significant profit increase (+33 and +36 percent respectively).

Figure 8 uses a split violin plot to show how net returns are distributed by crop and farming practice. The wider and elevated "violin" of sustainable farms graphically highlights the greater median returns along with reduced dispersion amongst adopters of SFPs. This implies that not only did sustainable practices enhance profitability, but also lowered the financial risk to farmers.

TABLE 8. NET RETURNS PER HECTARE (PKR) FOR SUSTAINABLE VS CONVENTIONAL FARMS

Crop	Conventional Farms (Avg. Net Return/ha)	Sustainable Farms (Avg. Net Return/ha)	% Increase in Net Return
Wheat	82,300	116,500	+41%
Cotton	91,200	121,300	+33%
Sorghum	75,600	103,200	+36%

FIGURE 8: NET RETURNS PER HECTARE BY CROP (VIOLIN PLOT)



The results obtained and discussed above indicate clearly that the adoption of SFPs in the semi-arid regions of Pakistan bring about agronomic, economic, and environmental reality. The increase in yield was similar in all three target crops and it increased with time implying that the soil health is improving cumulatively. The sustainable productivity has a solid basis in the improvement of SOC and availability of nutrients.

Especially remarkable and very much apply to the situation in Pakistan on the verge of the water crisis were the water-use efficiencies. The reduction of costs in synthetic inputs together with the rise in yield contributed to significant growths in the net farm returns and thus SFPs became an economically viable alternative.

Notably, these advantages were attained without compromising the long-term sustainability of the farming system - enhancing soil health, lessening reliance on inputs and increasing water-use efficiency. These results are mirrors to the larger ambitions of climate-smart and sustainable agriculture, and they give an excellent evidence base to facilitate the broader uptake of SFPs in semi-arid Pakistan.

DISCUSSION

This study findings leave no doubt that sustainable farming practices (SFPs) are a proven solution to increase crop productivity, enhance soil health, improve water-use efficiency, and improve farm profitability in semi-arid areas of Pakistan. The results provide useful empirical data to the existing body of literature regarding the potential of sustainable agriculture to resolve the compounded issues of food security, climate change, and natural resource degradation in dryland farming systems (Vanlauwe et al., 2019; Rockström & Karlberg, 2010).

The realized yield increases (37 percent in wheat, 28 percent in cotton and 33 percent in sorghum) are in line with the world experience on the advantages of conservation agriculture and integrated soil fertility management in semi-arid environments. Indicatively, Corbeels et al. (2020) found that conservation agriculture promoted a 2040% rise in maize yields in drylands of southern Africa. Likewise, experiments in Indian arid zones concluded that integrated nutrient management and minimum tillage raised the yields of sorghum and pearl millet by 2535 percent (Jat et al., 2019). The high yield increases registered in this experiment highlight the applicability of these measures to Pakistani dryland farming where yield stagnation in conventional systems is an alarming issue (Kassam et al., 2018).

One crucial factor that led to the yield gains recorded in this paper is the improvement of soil organic carbon (SOC) and soil nutrient condition under SFPs. The SOC increment of 0.63 to 0.77 percent in three seasons compares with meta-analysis outcomes indicating that conservation tillage, organic amendments, and diversified rotations have the potential to enhance SOC stocks in dryland soils remarkably (Powlson et al., 2014; Lal, 2020). Increased SOC has been shown to enhancing soil structure, water-holding capacity, and nutrient retention, which are all essential in facilitating resilient crop production in moisture-stressed environments (Oldfield et al., 2020).

The other significant aspect that led to yield increases was improved nutrient availability. The significant improvements in nitrogen, phosphorus, and potassium seen in sustainable farms are also similar to other dryland systems where integrated soil fertility management has been implemented (Vanlauwe et al., 2015). As an example, Amelung et al. (2020) stated that organic and mineral fertilization practices enhanced nutrient cycling and crop productivity in African semi-arid regions. Nutrient mining is a significant issue in Pakistan, where imbalanced fertilizer application and soil deterioration are causing severe problems (Zia et al., 2019), so the capacity of SFPs to restore the nutrient balance should be seen as a vital route to long-term sustainability.

One of the most dramatic findings of this study involved Water-use efficiency (WUE) increases. Drip and sprinkler irrigation technologies nearly doubled WUE in wheat and cotton and boosted it by 62 percent in sorghum. These returns are in line with the findings of other researchers in the Middle East and North Africa, who reported that precision irrigation could save 40 70% of water consumption without yield penalty (Frenken & Gillet, 2012; Oweis & Hachum, 2009). Precision irrigation technologies need to be scaled-up in semi-arid Pakistan where groundwater depletion and surface water scarcity are rapidly reaching a critical point (Qureshi, 2020).

The fact that SFPs lead to economic gains that are witnessed in this study further supports the notion that they are viable to smallholder farmers. The reduced input costs (especially synthetic fertilizers, pesticides, and irrigation) coupled with increased outputs yielded 33 41% increases in net returns. These outcomes are consistent with other research in sub-Saharan Africa and South Asia, stating that SFPs could enhance farm profitability and decrease input dependency (Pretty et al., 2011; Snapp et al., 2018). Notably, the split violin plot of net returns in the present study indicated not only the greater mean returns but also the less variety among SFP adopters, which indicates more economic resilience, which is also in line with Glover et al. (2016) research on agroecological practices in drylands.

In addition to yield and profitability, qualitative data obtained by talking with farmers participating in this study brought forward other advantages of SFPs, such as increased crop tolerance to drought and heat stress, enhanced soil workability, and elevated pest control. These results are in accordance with what the larger body of knowledge on ecosystem services concerning diversified and biologically active farming systems (Altieri et al., 2015; Tittonell, 2020). These services become especially valuable in semi-arid areas that experience rising climate variability and extreme weather conditions (Morton, 2007).

It can also be noted with interest the cumulative nature of the benefits that were observed in the three cropping seasons. The increasing yield gaps in favor of SFPs over time provide indications that the maximized potential of these practices can only be achieved after a few years of repeated use as the soil health improves and agroecological functioning stabilizes. This dynamic in time is properly-documented in long-term experiments in conservation agriculture (Derpsch et al., 2014) and it reveals the significance of assisting farmers during the initial period of transition.

Regardless of these encouraging findings, there are barriers to scaling up the adoption of SFP. Prohibitive initial investment in drip irrigation system was one of the major obstacles reported by farmers consistent with findings of other researchers (Burney & Naylor, 2012). It will be necessary to overcome this limitation through novel funding systems, including subsidies or microcredit, pay-as-you-go schemes (Wichelns, 2014). Likewise, technical knowledge gaps related to crop rotations, organic input management and irrigation scheduling need to be filled in through intensified extension services and through farmer-to-farmer learning networks (Maat & Glover, 2012).

Policy and institutional support will also play an important role. Pakistan Pakistan has a long history of input-intensive green revolution models as a priority in agricultural policies and extension programs, at the cost of sustainable systems (Rana & Sial, 2020). Changing this bias will entail a conscious effort to integrate SFPs into national agricultural policies through substantiation of their numerous advantages, as done in this study.

Lastly, it is worth noting that the results presented in this paper, though promising, are premised on three districts and three cropping seasons. The current study should be repeated on longer-term and larger-scales, as well as in more studies in the different semi-arid landscapes of Pakistan, to adequately evaluate the sustainability, scalability, and context-specific adaptations of SFPs in Pakistan. The synergies and trade-offs among various components of SFP also need to be investigated in the future because integrated systems approaches will present the most significant opportunities (Thornton et al., 2018).

To sum up, the current study presents robust empirical evidence of the transformative power of sustainable agricultural practices in the semi-arid areas of Pakistan. The reported increases in yield, soil health, water-use efficiency and profitability are consistent with what has been observed globally and highlights the necessity to adopt these practices at larger scale. Through this, Pakistan will be able to transform towards a more resilient, productive and sustainable agricultural future amidst the growing environmental and socio-economic pressures.

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