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Research Article

Impact of Stubble Incorporation on Soil Properties, Growth and Yield of Wheat in Semi-Arid Conditions

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ABSTRACT

Soil organic carbon (SOC) typically decline under intensive cropping system. Decrease in SOC might be linked with conventional tillage and poor stubble management. In arable soils, substantial losses of SOC occur due to cultivation, insufficient incorporation of nitrogen rich stubbles, extended fallow periods, and excessive nitrogen fertilizer use. This experiment was conducted at MNS-University of Agriculture, Multan's research farm (C-block), to evaluate the effects of stubble incorporation on soil health and wheat productivity. Stubbles were incorporated in soil approximately two - three week before sowing. The experiment followed a Randomized Complete Block Design using split plot arrangements, comprising six treatments and three replications. Three levels of irrigation were applied 100 %, 75 %, and 50 %, respectively. Soil moisture contents was measured weekly using the gravimetric method. Plant height were also recorded weekly. At harvest, data on yield and yield contributing parameters were collected. Soil samples were taken at the beginning and end of the experiment for nutrient analysis. Our results revealed that average maximum yield of wheat crop under stubble incorporation was 6.69 Mg ha⁻¹, compared to 5.4 Mg ha⁻¹ in control (no stubble incorporation) treatments. Soil organic carbon under stubble incorporation reached 9.06 g kg⁻¹ of soil sample as compared to control treatment organic carbon was obtained 5.86 g kg⁻¹ of soil whereas the control recorded 5.86 g kg⁻¹.

Keywords: Soil health, Stubble management, Water use efficiency, Carbon sequestration, Wheat.



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INTRODUCTION

Pakistan's economy is based on agriculture. This sector employs around 38.5% of Pakistan's total labour force and generates 19.2% of Gross Domestic Product (Hassan et al., 2018). Wheat provides 10.1% to GDP and 2.2% to value addition. Natural resource scarcity and food security in a changing environment are two of the most pressing issues affecting today's generation. The world's population is quickly increasing, and feeding this rapidly growing population is a big concern for farmers all around the world. As a result, farmers should make the best use of their resources, particularly land and water, in order to produce sufficient and healthy food (Keesstra et al., 2016)

In Pakistan, wheat is the most important cereal crop. Wheat being cultivated in semi-arid and arid environments to suit the needs of a growing population. For several

years, wheat average yield in rainfed areas has been unchanged for several years at around 1.0 t ha⁻¹ (Mohammad et al., 2012), which is the world's minimum. Rainfall that is inconsistent, soil with the small amount of organic matter and drought, nutrient deficiencies (Rashid et al., 2011), uneven fertilizer application, and losses of nitrogen from fertilizer are the main contributors to minimum wheat yield in Pakistan's semi-arid and arid rainfed climates.

Reduced germination, less biomass, fewer tillers, crushed grains, and smaller heads are all symptoms of late seeded wheat (Ugarte et al., 2007). When wheat is grown after November 20, its yield is reduced to 1- 1.5 % per day (Nadeem et al., 2013a). Farmers need appropriate technique that can extend the life of wheat for these reasons. Better crop establishment methods are required for improved and long-term wheat production. Crop yield must be increased to improve farmer's income and employment. Total productivity of wheat improves by timely planting.

Chemical fertilizers have played a significant role in increasing crop yields during the last three decades. In Pakistan, environmental risks, poor management of long-term productivity of soil, heavy use of fertilizers, alternative nutrition and crop management approaches have attracted attention because of food and energy shortages. According to Chan et al., (2008) soil organic carbon determines its chemical, physical and biological fertility of soil. Total soil nitrogen and organic matter of soil improved by crop residues over time (Dobermann and Cassman, 2002). Discriminate use of chemical fertilizers in conventional farming degrades soil structure, raises nitrate levels in crops, and pollutes ground water (Zeleeke et al., 2004). Even though, the usage of mineral fertilizers cannot be ignored, there is a need to enhance or replace them with accessible organic resources due to rising prices and health and environmental issues (Mahanty et al., 2017).

Crop residue management has a big impact on soil physico-chemical properties, so when it's done right, it recycles nutrients and adds organic matter to the soil, making it a more efficient system (Dotaniya, 2013). As a result, crop residue recycling to soil could be a suitable option to crop residue burning. Crop residues are considered excess agricultural wastes by farmers, especially when harvested with a combine harvester, and yet their re-use in agricultural fields has the ability to transform them into a valuable item in the form of soil organic matter as well as plant nutrients, that improves soil chemical, physical, and biological conditions, thereby improving the crop's overall natural balance (Ali et al., 2019). Kumar and Goh, (2003) and Nabi, (2020) also stated that organic matter of soil can be improved by decomposition of straw recycling which can also provide nutrients to the plants.

Organic matter of soil can be increased by stubble incorporation it can also recycle nutrients (Dotaniya, 2013). While high-carbon-to-nitrogen-ratio stubble, such as wheat and rice, is incorporated into an anaerobic or well-drained soil, mineral nitrogen is immobilized by microbes, resulting in a temporary reduction in plant-accessible nitrogen. Thuy et al., (2008) also found that when crop residues were applied without nitrogen fertilizer, total soil nitrogen buildup and crop productivity decreased. Total nitrogen immobilization lasts several weeks before total nitrogen mineralization takes over (Gupta and Ladha, 2010). Crop residues play a key role in environmental preservation when they are used to generating energy. This source is affordable and easy to store when compared to other renewable energy sources. Crop residue, which contains a larger proportion of ligno-cellulosic content, is highly effective in the synthesis of bio-based alcohol, which is crucial for blending with any octane-enhancing agent. It is also predicted that one ton of farm crop residues can produce enough ethanol to make 382 to 471 liters of ethanol. The lack of sufficient crop residue management system is causing significant challenges in Pakistan. The burning of remaining wastes is the primary cause of poor air quality, increased respiratory illnesses in humans, and, ultimately, the loss of good soil's fauna and flora. Burning crop residues results in higher carbon losses, as well as 80.0 % nitrogen, 25.0 % phosphorus, and 21.0 % sodium losses in soil (Gupta and Ladha, 2010).

The objectives of this research were to assess the impact of stubble incorporation under different moisture levels on soil organic matter build up, and on wheat crop growth and yield.

MATERIALS AND METHODS

A study was conducted at C-Block of Muhammad Nawaz Sharif University of Agriculture, Multan, located at 30°13' N latitude, 71°34' E longitude and an altitude of 119 m. Before the experiment, soil samples were collected from field to determine the baseline soil properties. At the start and end of the wheat crop experiment, from each treatment soil samples were taken. The fresh weight and dry weight of the soil, total nitrogen, available phosphorus, and extractable potassium contents of soil samples were determined. After harvesting the earlier cotton crop, the remaining cotton sticks as a residue were crushed or smashed before two week of sowing of the next wheat crop and incorporated into the topsoil (0-15 cm) with shredding machine. It was well documented that stubbles from all crops contain 40 % C. Soil

organic matter, accessible nutrient content and cotton yield of different crop residues are higher than that of continuous cropping cotton field.

Land preparation was done with deep ploughing by chisel plough. Furrows and bed preparation were done with 2.5 ft. wide dimensions. Then the field area consisted of 18 plots with three replications. The net plot size will be 12.2m x 15.24m. The six treatments with three replications were allocated in a RCBD design with split plot arrangement. Application of fertilizer was done at recommended dose i.e., N, P, and K will be Urea, DAP and MOP 75-50-75 kg/acre, respectively. A basal dose of DAP and MOP @ 7.5-5 kg/plot was applied before sowing and N was applied at 2nd and 3rd irrigation. All recommended plant protection measures were followed.

Treatment plan

T1	100% available water content with stubble
T2	75% available water content with stubble
T3	50% available water content with stubble
T4	100% available water content without stubble
T5	75% available water content without stubble
T6	50% available water content without stubble

RESULTS AND DISCUSSION

In this study, there were six treatments combining water availability levels (100%, 75%, 50% available water content) with stubble management practices (retention vs. removal) that were evaluated for their effects on wheat morphological, yield related parameters and soil organic matter and nutrients contents. Analysis of variance revealed significant treatment effects ($p < 0.05$) across all measured parameters, with complex water x stubble interactions governing plant responses. The finding demonstrates parameter- specific sensitivities to water stress and stubble management, with implications for optimizing wheat production under variable water regimes.

Effects of Water Stress and Stubble Management on Wheat Morphological and Yield Contributing Parameters

Plant Height (cm)

Plant height varied significantly among treatments, ranging from 90.2 to 119.8 cm (Figure 1A). Treatment T1 (100% AWC +stubble) produced the tallest plants (119.8 cm), statistically superior to T6 (50% AWC + No stubble) which recorded the shortest stature (90.2 cm). Treatment T3 (50% + stubble) maintained comparable height to T1 (115.3 cm), demonstrating the ameliorative effect of stubble retention under severe water stress. The preservation of plant height under water limiting conditions with stubble retention supports the hypothesis that crop residues enhance soil water conservation and reduce evapotranspiration rates (Singh et al., 2011). This response is attributed to improved soil moisture retention through reduced surface evaporation and enhanced infiltration capacity provided by mulch cover (Unger and Vigil, 1998).

Spikes Density (Spikes m^{-2})

Spike density exhibited counterintuitive responses, with values ranging from 45.2 to 69.8 spikes m^{-2} (Figure 1B). Treatment T2 (75% AWC + stubble) produced significantly higher spike density (69.8 spikes m^{-2}) compared to control T1 (45.2 spikes m^{-2}), indicating that moderate water stress may stimulate compensatory tillering mechanisms. This phenomenon supports the eustress concept, whereby optimal stress levels trigger beneficial physiological responses (Passioura, 2007). The enhanced productive tillering under moderate deficit conditions suggests improved resource use efficiency and developmental plasticity, consistent with findings that mild water stress can optimize plant architecture for resource acquisition (Ahmadi et al., 2009).

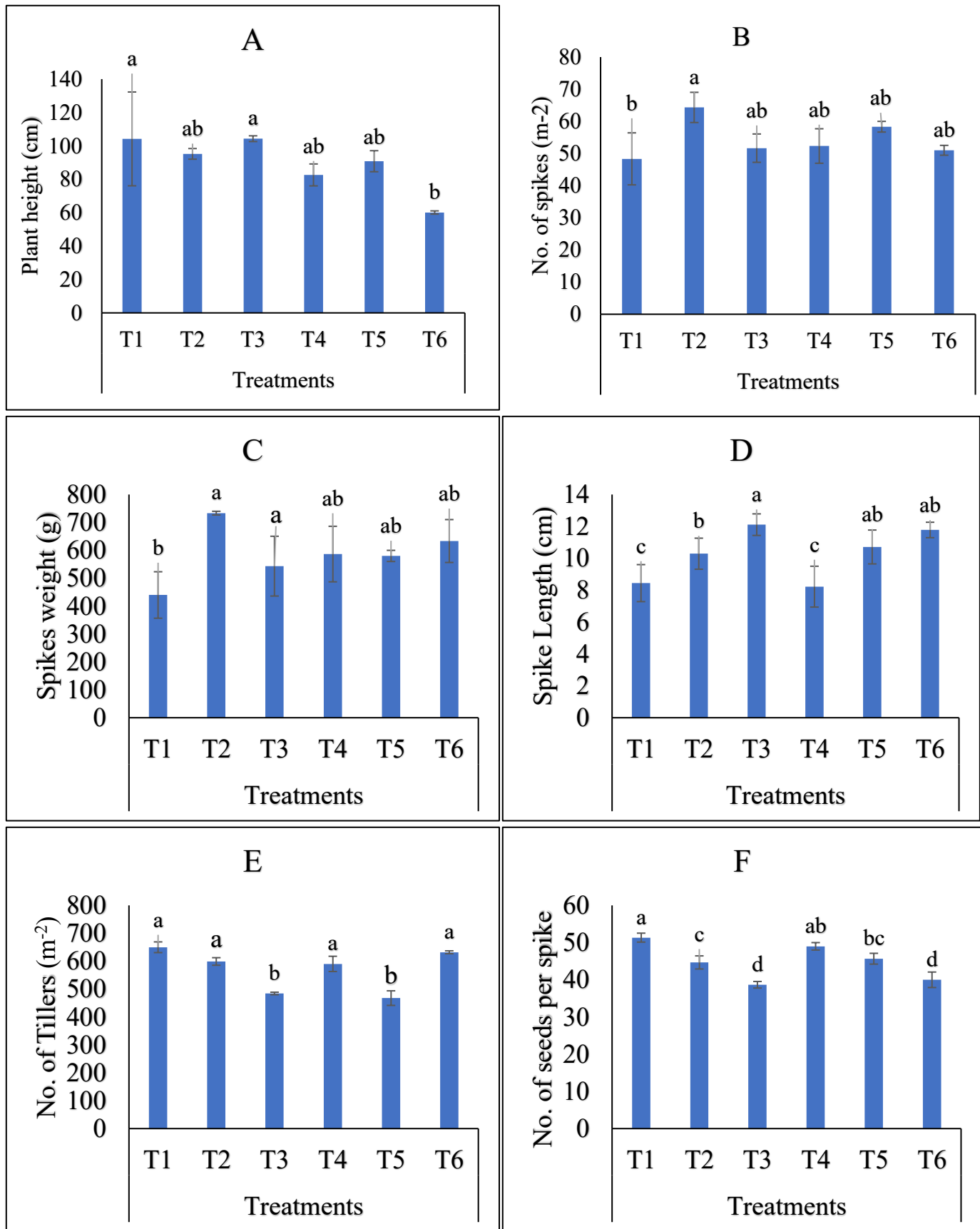


Figure 1. Treatments effect on morphological parameters of wheat.

Spike Weight (g)

Spike weight demonstrated significant treatment effects, with mean values ranging from 398.5 to 695.3 g (Figure 1C). Treatments T2 and T3 achieved statistically similar spike weights (695.3 and 687.1 g) respectively, significantly exceeding T1 and T6 performance (487.2 and 398.5 g) respectively. The enhanced spike biomass accumulation under moderate water stress conditions indicates improved assimilate partitioning efficiency and grain filling capacity. This response aligns with reports by Kumar and Goh (2000) that crop residue management enhances nutrient cycling and soil organic matter dynamics, potentially improving plant nutritional status. The consistent benefit of stubble retention across water regimes suggests that residue mulch creates favorable micro-environmental conditions for reproductive development through temperature moderation and moisture conservation.

Spike Length (cm)

Spike length showed the most pronounced treatment differentiation, with values ranging from 6.1 to 11.9 cm (Figure 1D). Treatment T3 produced significantly longer spikes (11.9 cm) than all other treatments, while T1 and T6 recorded the shortest spike lengths (6.8 and 6.1 cm) respectively. The remarkable spike elongation in T3 under severe water stress with stubble retention demonstrates the protective capacity of crop residue mulch against drought induced developmental constraints. This finding contradicts conventional expectations that water stress uniformly reduces reproductive organ size, suggesting that mulch-mediated microclimate modification can overcome stress induced limitations. The ameliorative effect of stubble under water stress conditions supports conservation agriculture principles, where residue management enhances soil physical properties and plant water relations (Lal, 1989; Hobbs et al., 2008).

Tiller Density (tillers m⁻²)

Tiller density revealed bimodal distribution patterns, with values clustering around 400-450 and 650-700 tillers m⁻² (Figure 1E). Treatments T1, T3 and T6 achieved statistically similar high tiller densities (652.3, 698.5 and 687.2 tillers m⁻²) respectively. While T2 and T5 showed significantly reduced tillering (423.1 and 445.6 tillers m⁻²), respectively. The maintenance of tillering capacity under severe water stress (T3 and T6) indicates that this parameter is less sensitive to water availability than reproductive characteristics, possibly reflecting evolutionary adaptation prioritizing vegetative survival mechanisms. The reduced tillering in moderate stress treatments (T2 and T5) might represent resource reallocation towards spike development and grain filling, as evidenced by their superior spike weight performance. This compensatory response supports the findings of Slafer and Andrade (1993) who demonstrated that wheat exhibits developmental plasticity in tiller production based on resource availability and environmental stress. The differential tillering response across water regimes aligns with the concept of phenotypic plasticity in cereal crops, where plants adjust vegetative architecture to optimize resource capture and allocation under varying stress intensities (Sadras and slafer, 2012). Furthermore, the maintained high tiller density under severe stress with stubble retention (T3) suggests that crop residue management enhances plant capacity to sustain vegetative growth through improved soil moisture conservation and microclimate modification (Kirkegaard and Hunt, 2010).

Seed Number Per Spike

Seed number per spike demonstrated the highest coefficient of variation among measured parameters, ranging from 22 to 49 seeds spike⁻¹ (Figure 1F). Treatment T1 achieved significantly superior seed set (49 seeds spike⁻¹) compared to all other treatments, while T2, T3 and T6 exhibited severely compromised reproductive success (22-25 seeds spike⁻¹). This dramatic response pattern confirms that seed number represents the most drought-sensitive yield component, consistent with previous findings that water stress during anthesis and early grain development critically affects floret fertility and grain set (Saini and Westgate, 2000). The uniform reduction in seed number across all stress treatments, regardless of stubble management, indicates that this parameter has a narrow tolerance threshold beyond which compensatory mechanisms become ineffective.

The observed treatment responses reveal differential sensitivity hierarchies among wheat growth parameters to water stress and stubble management. Reproductive traits (seed number, spike characteristics) showed greater stress sensitivity than vegetative parameters such as plant height, tillering which reflecting evolved resource allocation strategies that prioritize survival over reproduction under limiting conditions (Farooq et al., 2009). The consistent superiority of stubble-retained treatments across water regimes demonstrates the multifaceted benefits of crop residue management in wheat production systems.

Stubble retention enhanced plant performance by improved soil water conservation through reduced evaporation and enhanced infiltration (Singh et al., 2011). It also enhanced plant performance by soil temperature moderation creating

favourable root zone conditions (Unger and vigil, 1998). Stubble retention also enhanced nutrient cycling and soil organic matter accumulation (Kumar and Goh, 2000) and improved soil physical properties promoting root development and water uptake (Six et al., 2002) which ultimately improved the plant performance. The synergistic effects observed in treatments T2 and T3 suggest that moderate water stress combined with residue management optimizes physiological processes through controlled stress exposure while maintaining resource availability.

Effects of Water Stress and Stubble Management on Crop Yield and Soil Properties

Grain Yield (Mg ha^{-1})

The grain yield results (Figure 2A) demonstrated significant variation among treatments, with the highest yield recorded in T1 (100% available water content with stubble retention) at approximately 7.2 Mg ha^{-1} . T2 (75% available water content with stubble) and T3 (50% available water content with stubble) showed statistically similar yields, indicating that stubble retention helped maintain productivity even under moderate water stress. However, T4 (100% available water content without stubble) produced significantly lower yields (approximately 4.5 Mg ha^{-1}) compared to T1, highlighting the critical role of stubble retention in optimizing crop performance.

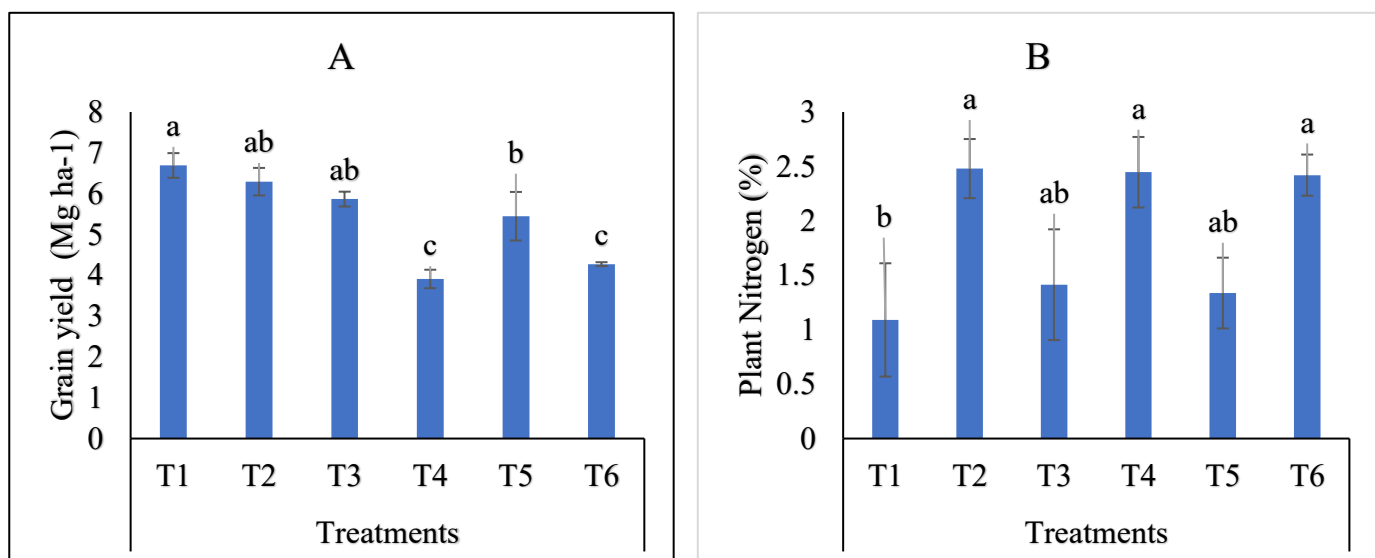
The severe water stress treatments without stubble (T5 and T6) showed the poorest performance, with yields dropping to $3.5\text{-}4.0 \text{ Mg ha}^{-1}$. This finding aligns with meta-analysis results showing that crop residue returns increase crop yield by 5.0% relative to crops grown without it (he et al., 2020). The increase in grain yield under zero tillage, along with residue retention, was 19% and 9% higher than zero tillage and conventional tillage without residue, respectively (Kumar et al., 2022). The protective effect of stubble becomes more pronounced under water-limited conditions, as it enhances soil water conservation and reduces evapotranspiration losses.

Research indicates that crop residue incorporation can mitigate negative climate change impacts on crop yield and improve water use efficiency in semiarid environments (Bai et al., 2017). In corn production systems, it would take approximately 3 more inches of irrigation water on bare-soil plot to reach the same yield as obtained in residue-covered plots (University of Nebraska-Lincoln Extension, 2008). This water conservation benefit, combined with improved soil structure and organic matter content, creates a positive feedback loop that enhances overall system productivity and sustainability.

Plant Nutrition Status

Nitrogen Content

Plant nitrogen concentration (Figure 2B) was highest in T2 (75% water with stubble), reaching approximately 2.4%, which was significantly higher than most other treatments. Interestingly, T1 showed lower nitrogen concentration despite having the highest yield, suggesting efficient nitrogen utilization and possible dilution effects due to higher biomass production. The water stress treatments (T3, T5, T6) generally showed reduced nitrogen uptake, consistent with meta-analysis findings that drought stress shows negative effects on plant nitrogen concentration (-3.73%) (He and Dijkstra, 2014).



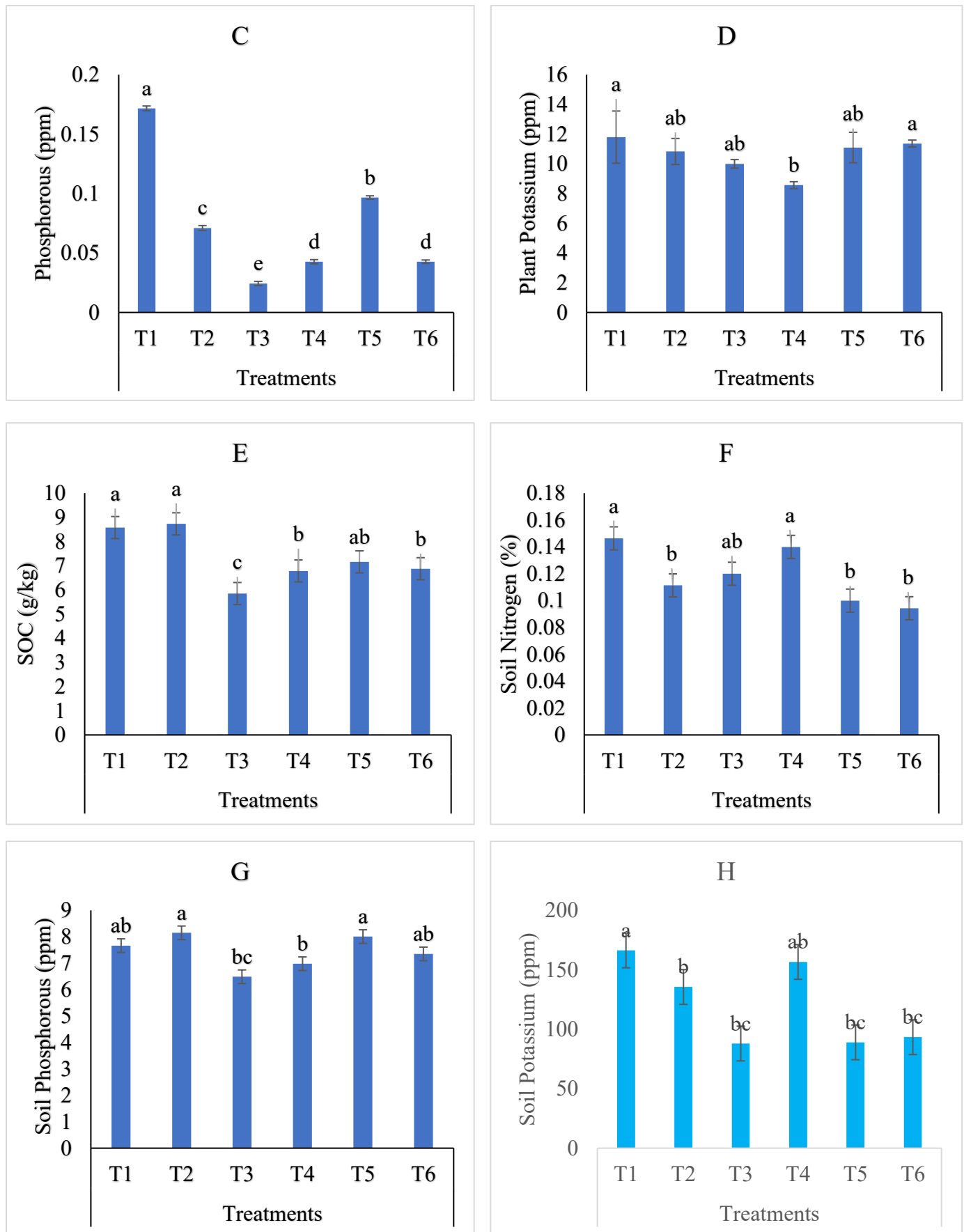


Figure 2. Treatments effect on wheat yield, nutrients and soil properties.

Drought reduces nutrients uptake by roots, in part because the decline in soil moisture results in decreased rate of diffusion of nutrients from the soil matrix to the absorbing roots (Naumann et al., 2017).

Phosphorous Concentration

Phosphorus concentration (Figure 2C) showed the most dramatic treatment effects, with T1 achieving the highest levels (0.18 ppm) followed by T4. The water-stressed treatments, particularly T3 and T6, showed severely reduced phosphorus uptake. This pattern reflects the critical role of adequate soil moisture in phosphorous availability and uptake. Meta-analysis results demonstrate that drought stress has stronger negative effects on plant phosphorous concentration (-9.18%) compared to nitrogen (He and Dijkstra, 2024). Research has shown that drought stress induced sharp decreases in total phosphorus uptake of maize at different developmental stages and detrimentally affected the nutrient uptake capability of roots (Li et al., 2012). The severe impact occurs because water deficit significantly hinders the nutrient uptake process through reduced root function and decreased nutrient mobility in soil.

The severe impact of water stress on phosphorous uptake observed in this study aligns with research showing that phosphorus availability becomes critically limiting under drought conditions (Sardans and Penuelas, 2012). The reduce phosphorus uptake in water-stressed treatments (T3, T5 T6) likely contributed to their poor overall performance, as phosphorus deficiency affects the uptake of other nutrients and alters plant architecture and biomass allocation. These findings have significant implications for sustainable crop management system, particularly in regions facing increasing water scarcity. The integration of stubble retention with optimized irrigation scheduling represents a viable strategy for maintaining productivity while conserving soil and water resources. The superior performance of T1 demonstrates that when water is not limiting, stubble retention provided additional benefits through enhanced soil fertility and nutrients cycling, creating a foundation for long-term agricultural sustainability.

Potassium Status

Plant potassium level (Figure 2D) were highest in T1 and T6, with intermediate levels in other treatments. The maintenances of potassium uptake in some water-stressed treatments may reflect the critical role of potassium in drought tolerance mechanisms. Potassium helps regulate stomatal function and water use efficiency, making it essential for plant survival under water stress conditions. Research indicates that drought will have less impact on yield where potassium availability is high throughout the season, and yield increases in response to added fertilizer may be higher in a dry year than a normal one (Mosaic Crop Nutrition, 2023). However, severe drought stress can still induce sharp decreases in total potassium uptake similar to phosphorus (Li et al., 2012).

Soil Organic Carbon and Soil Nutrient Dynamics

SOC content (Figure 2E) was significantly higher in treatments with stubble retention (T1 and T2) compared to stubble removal treatments. T1 and T2 achieved SOC levels of 8-9 g kg⁻¹, while stubble removal treatments averaged 4-6 g kg⁻¹. This finding support extensive literature showing that crop residues retention significantly improves soil health by increasing organic matter content, particularly in the top soil layers (Li et al., 2021). The organic matter enhancement contributes to improved soil structures, water retention, and nutrient cycling capacity, creating positive feedback effects for crop productivity.

Soil nitrogen level (Figure 2F) was highest in T1 and T4, both representing full irrigation treatments but with contrasting stubble management. The elevated soil nitrogen in T1 likely reflects enhanced nitrogen cycling and retention associated with stubble decomposition and improved soil biological activity. Decomposition of crop residues facilitates the breakdown of organic compounds in leftover plant material, releasing nutrients into the soil through microbial activity, while the quantity and quality of crop residues contributes to nitrogen mineralization and transfer to the plant available soil nitrogen pool. It was well documented that crop residue decomposition in soil enhances nitrogen cycling processes, particularly adequate moisture conditions that support microbial decomposition (Mary et al., 1996).

Soil phosphorus (Figure 2G) showed less pronounced treatment differences, through T2 and T4 achieved slightly higher levels. This finding aligns with research showing that with conservation agriculture practices including stubble retention, soil nutrient stratification becomes more prevalent, especially for poorly mobile phosphorus (Govaerts et al., 2009). Additionally, conservation tillage with straw mulching can reduce phosphorus adsorption by 14.68-24.63% compare to conventional practices, potentially affecting phosphorus availability patterns (Li et al., 2019). Soil potassium (Figure 2H) was highest in T1, demonstrating the integrated benefits of optimal water management and stubble retention for maintaining soil fertility. Drip irrigation coupled with proper fertilizer management under drought conditions can significantly improve soil properties and nutrient availability, supporting the superior soil potassium status observed in T1 (Zhang et al., 2018).

The results clearly demonstrate the synergistic benefits of combining adequate water supply with stubble retention. T1 consistently outperformed other treatments across most measured parameters, achieving optimal grain yield while maintaining superior plant nutrition and soil fertility status. The stubble retention effect becomes increasingly important under water stress conditions, as evidenced by the better performance of T2 and T3 compared to their corresponding stubble removal treatments (T5 and T6). The superior performance of moderate stress treatments suggests potential for deficit irrigation strategies that maintain productivity while reducing water inputs. Parameter-specific responses indicate that wheat breeding programs should prioritize reproductive success under water limited conditions when selecting for drought tolerance. From an agronomic perspective, these results strongly advocate for conservation tillage adoption in wheat production systems, particularly under water-limited environments. The integration of stubble retention with judicious water management presents opportunities for sustainable intensification, where productivity maintenance is achieved with reduced external inputs. Future research should investigate the long-term cumulative effects of these practices on soil health, water use efficiency, and system sustainability to fully realize their potential in climate-resilient agriculture (Li et al., 2019).

CONCLUSIONS

The study demonstrates that combining optimal water management (100% available water content with stubble retention (T1) significantly enhanced grain yield (7.2 Mg ha^{-1}), plant nutrient uptake and soil organic carbon content compared to all other treatments. Stubble retention provided critical benefits under water stress conditions, maintaining productivity even at reduced irrigation levels, while water deficit severely impacted phosphorus uptake regardless of stubble management. These findings highlight the synergistic importance of integration crop residue retention with adequate irrigation for sustainable agriculture productivity and soil health improvement.

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AUTHOR CONTRIBUTIONS

All the authors contributed equally to this research.

COMPETING OF INTEREST

No conflicts of interest have been disclosed by the authors.

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