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Soil-mediated Effects of Rice Residue Burning on Wheat Physiology and Productivity under Screen-house Pot Conditions

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Abstract: Rice residue burning is widely practiced to facilitate rapid field preparation for the succeeding crop, despite concerns regarding its adverse environmental effects and its potential to alter soil properties that influence sustainable crop production. The present study evaluated the soil-mediated effects of rice residue burning on the physiology and productivity of wheat grown under screen-house pot conditions. Soil samples (0–15 cm depth) were collected from nine sites before and after rice residue burning and used to establish a completely randomized pot experiment comprising 18 treatments with three replicates (54 pots). Wheat physiological parameters, including relative water content (RWC), chlorophyll content, chlorophyll fluorescence, photosynthetic rate, transpiration rate and stomatal conductance, together with yield attributes and productivity, were assessed and analysed statistically. Wheat grown in post-burning soils exhibited significant ($P < 0.05$) reductions in physiological performance and productivity compared with wheat grown in pre-burning soils. The maximum reductions recorded under post-burning conditions included 17.6% in RWC, 21.6% in chlorophyll content, 17.7% in chlorophyll fluorescence, 31.7% in photosynthetic rate, 33.2% in transpiration rate and 36.1% in stomatal conductance. Similarly, grain weight per spike, number of grains per spike, grain yield and biological yield decreased by up to 29.0%, 26.3%, 24.5% and 28.0%, respectively. These findings demonstrate that changes in soil following rice residue burning adversely affected wheat physiological performance and productivity under screen-house pot conditions. The study highlights the importance of adopting sustainable rice residue management practices to minimize soil degradation and support crop productivity, while further field-based investigations are required before extrapolating these findings to field-scale wheat production.

Keywords: Rice residue burning, Soil-mediated effects, Wheat physiology, Grain productivity

1. INTRODUCTION

India's primarily agrarian society engages more than half of its population, around 54.6%, in agricultural and associated activities. Presently, this cultivation method is prevalent across diverse Indian states, including Punjab, Haryana, Uttar Pradesh, Bihar, and Madhya Pradesh, which are the frontrunners. Collectively, these states account for 75% of the country's food output (Ullah et al. 2021). Rice, wheat, and maize stand as the primary cereal crops globally, with rice serving as the most crucial staple food for over 60% of the world's population. The Asian region, including India, contributes significantly, accounting for about 90% of the world's rice production and consumption (Krishna and Meenakshi, 2022). Rice plays a pivotal role in Indian agriculture, serving as the staple food for over 70% of the population and acting as a vital source of livelihood for rural households. In India, rice cultivation holds a prominent position, occupying approximately 478 lakh hectares in the year 2022-23 (FAS, 2025). As a predominantly agrarian nation, India heavily relies on its agricultural system, leading to the generation of significant quantities of crop residues. Specifically, the rice-wheat cropping system contributes approximately one-fourth of the nation's total crop residue output (Bhuvaneshwari et al. 2019). **Various methods are available for managing these residues, such as burning, baling, incorporating them into the soil in situ, removing residues, or using them for mulching, animal feed, or bedding. However, burning is often favored by farmers due to its convenience and cost-effectiveness in swiftly clearing fields (Dutta et al. 2022). Alternative methods for residue utilization includes composting, mushroom cultivation, and biofuel production with good economic value (Kaur *et al.* 2022).** The burning of rice straw emits a range of gases, such as carbon dioxide (70%), carbon monoxide (7%), methane (0.66%), and nitrous oxide (2.09%), which have detrimental effects on air quality and the well-being of humans and animals (Jain et al. 2014). This smoke can mix with fog, leading to the formation of smog, and presenting hazards to both human health and the surrounding ecosystem (Chawala and Sandhu, 2020). Different methods of managing residues, including burning, have a notable impact on the physico-chemical characteristics of soil, influencing parameters such as bulk density, total NPK, soil organic matter (SOM), pH, and EC. Additionally, long-term effects such as erosion, reduced organic matter content, and compromised aggregate stability gradually manifest as the soil surface undergoes erosion from wind and water. These alterations are compounded by the decline in organic matter caused by stubble burning (Abdurrahman et al. 2020). Rice straw burning has detrimental effects on soil health, inducing degradation in soil properties and negatively impacting plant and soil ecology (Parihar et al. 2023). This practice notably elevates soil temperature, reaching 33.8°C–42.2°C at a depth of approximately 1 cm (Gupta et al. 2004). These elevated temperatures lead to the depletion of nitrogen in various forms from the soil, ranging from 23% to 73%, causing rapid changes in the soil's carbon-to-nitrogen (C: N) ratio in its upper layers (Kumar et al. 2015). **The rise in total potassium content could result from the leaching of extractable potassium and cation mineralization from burnt crop residue. The pH elevation might result from soil ash deposition or the generation of sodium and potassium oxides, hydroxides, and carbonates on the soil surface. The increased EC could be attributed to ash-induced aggregation collapse and void obstruction by dispersed ions.** Consequently, rice straw burning in fields results in diminished soil health, leading to decreased yields (El-Sobky, 2017; Abdurrahman et al. 2020).

CO_2, N_2O, and CH_4 are the most significant greenhouse gas (GHG) emissions as a result of crop burning. The global warning potential of CH_4, N_2O are 21 and 310 times greater than that of CO_2 (Chataut et al. 2023). Releases of NOx, leading to the formation of ground-level ozone through the interaction of nitrogen oxide and volatile organic compounds with solar radiation. This ozone adversely affects plant metabolism, contributing to decreased crop productivity for wheat, rice, cotton, and soybeans in India. Ground-level ozone infiltration damages plant leaves and hampers their metabolic processes. Particularly in northern India, studies indicate significant detrimental effects on wheat and soy crops due to ozone exposure (Sharma *et al.* 2019). Compelling empirical data demonstrates that air pollution stemming from the burning of rice residue significantly impacts food production (Abdurrahman *et al.* 2020). India has incurred an estimated economic loss of approximately USD 1.5 billion over the past five years due to crop residue burning (IFPRI, 2019). A recent independent study highlights that stubble burning in Punjab and Haryana has led to reduced agricultural productivity. Elevated levels of fine particulate matter and NO_2 were observed at the end of the Kharif season in these regions, primarily due to extensive rice biomass burning (Abdurrahman *et al.* 2020). In India, certain states levy monetary fines on farmers to discourage crop residue burning (CRB) practices, as continuous CRB practices over time have been found to diminish agriculture productivity (Garg *et al.* 2022). From the information gathered, it is evident that stubble burning detrimentally affects agricultural productivity. Implementing effective measures to mitigate these effects is crucial for enhancing agricultural productivity to meet the growing food demand. However, there is currently a lack of research data in the literature specifically addressing the impact of stubble burning on the physiology and productivity of subsequently grown wheat crops. Keeping in view the above concern, the present study was conducted on the impact of rice crop residue burning on physiology and productivity of succeeding grown wheat crop and results are discussed.

2. Materials and Methods

2.1. Soil sampling and analysis

Soil samples were collected on 21 October 2021 from the pre-burning (one day before residue burning) and post-burning (One day after residue burning) fields at spatially paired nine sites in Tohana, Fatehabad, Haryana, India. Soil samples were collected from three villages—Khardwal, Samain, and Bithmara—with three sampling sites selected in each village and three replications collected from each site (Fig 1). For both the pre-burning and post-burning fields, ten soil cores (0–15 cm depth) were collected from each sampling site using a soil auger and thoroughly mixed to obtain a homogeneous composite sample of approximately 10 kg for each experimental pot. In total, 54 composite soil samples were prepared for the 54 experimental pots. No fertilization, irrigation, tillage, or rainfall occurred between the two sampling events. The collected soil samples were air-dried at room temperature, gently crushed, and passed through a 2-mm sieve before analysis. Soil pH and electrical conductivity (EC) were measured in a 1:5 (w/v) soil-to-distilled water suspension using a microprocessor pH–EC meter (Model 1611). Soil organic carbon was determined by the Walkley and Black (1934) wet oxidation method, and soil organic matter (%) was calculated by multiplying the organic carbon content by the Van Bemmelen conversion factor (1.724). Total nitrogen was determined by the Kjeldahl digestion method (Bremner and Mulvaney, 1983). Total phosphorus was determined after nitric acid–perchloric acid (4:1, v/v) digestion of soil samples, followed by colorimetric determination using the molybdenum blue method described by Rowland and Haygarth (1997). Total potassium was determined from the same diacid digest using a flame photometer.

Figure 1: Geographic coordinates of soil sampling sites and field status during pre- and post-burning periods

2.2. Experimental design

Experiment was conducted during Rabi season (2021-22). Pots study was conducted to find the effect of burnt soil on wheat. Pot were filled with collected soil and then wheat was sown in pots. **Standard plastic pots (approximately 30 cm top diameter × 26 cm height) were filled with 10 kg of soil collected from each sampling site before and after rice residue burning. Wheat (*Triticum aestivum* L.) cultivar WH 1105 was sown on 9 November 2021, with 8–10 seeds per pot**. **After seedling establishment, the plants were thinned to five healthy plants per pot, which were maintained until harvest. Pots were irrigated** as required **to maintain suitable soil moisture, and no fertilizers were applied during the experimental period. Each pot represented the experimental unit, while measurements recorded from five plants (or leaves) within the same pot were considered subsamples. The values obtained from these plants were averaged to generate a single observation for each pot prior to statistical analysis.** The experiment consisted of **18 treatments** (nine sampling sites × two burning conditions), each replicated **three times**, resulting in a total of **54 experimental pots** arranged in a completely randomized design. Physiological measurements were recorded from the **same pots** at both the **vegetative** and **heading** stages. **Measurements were performed on the youngest fully expanded leaf during the vegetative stage and on the flag leaf during the heading stage. The experiment was conducted under natural screen-house conditions without artificial control of temperature, relative humidity, or light. Meteorological data (maximum and minimum temperature, relative humidity, rainfall, and bright sunshine hours) for the experimental period were obtained from the Department of Meteorological Sciences, CCS Haryana Agricultural University, Hisar. The data obtained from wheat grown in pre-burning and**

post-burning soils were analyzed separately using two-factor analysis of variance (ANOVA), considering sampling site and growth stage as fixed factors. Mean separation was performed using Tukey's honestly significant difference (HSD) test at the 5% level of significance. Physiological parameters and yield attributes were examined for the wheat grown in both pre-burnt and post-burnt soil in pots under screen house conditions.

2.3. Parameters Analysis

2.3.1. Relative water content

Relative water content (RWC) of the leaf was assessed using the technique introduced by Barrs and Weatherley, (1962). Immediately after excising leaf samples, they were weighed and placed in Petri dishes containing approximately 20 ml of distilled water. The samples were then kept at a constant temperature under diffused light conditions for a duration of 4 hours. Once the leaves reached full turgidity, they were removed from the petri plates. Any excess water was removed by gently blotting with coarse filter paper, and the leaves were weighed again to determine their turgid weight. Subsequently, the samples were placed in an oven to obtain their dry weight, which was then recorded. RWC was calculated by the following formula:

$$RWC (\%) = \{Fresh\ weight\ (FW) - Dry\ weight\ (DW) / Turgid\ weight\ (TW) - Dry\ weight\ (DW)\} \times 100$$

2.3.2. *Chlorophyll content*

In accordance with the approach outlined by Zhao et al. (2007), the SPAD chlorophyll content was determined using a chlorophyll meter, specifically the Minolta SPAD-502 Plus model. This device assessed the greenness or relative chlorophyll content of the leaves. The device provides immediate and non-invasive measurements on a plant, utilizing the assessment of light intensity absorbed by the tissue sample, primarily at a peak wavelength of about 650 nm (red LED). Additionally, a secondary peak at around 940 nm (infrared LED) is emitted concurrently with the red LED to account for leaf thickness.

2.3.3. Chlorophyll fluorescence

Chlorophyll fluorescence readings, including F0, Fm, and Fv/Fm, were captured at a distance of 4 cm from the base of the underside of leaves using a chlorophyll fluorometer (Opti-Sciences Model OS-30p). Each replication involved the measurement of five randomly chosen plants. Initially, the leaf was placed in darkness for one minute, and secured with clips for acclimation. Subsequently, dark-adapted samples were exposed to continuous irradiation for 1 second at an intensity of 1500 μ mol $m^{-2}s^{-1}$, emitted by an array of three light-emitting diodes within the sensor. This irradiation included 695 nm modulated light directed towards the leaf. The resulting fluorescence signals, comprising F0, Fm, and Fv/Fm, were then detected.

2.3.4. Photosynthetic rate, Transpiration rate and Stomatal conductance

From 10:30 AM to 11:30 AM, the photosynthetic rate (μmol m^{-2} s^{-1}), transpiration (mmol $m^{-2}s^{-1}$), and stomatal conductance (**mol $m^{-2}s^{-1}$**) of the leaf were measured using an open system LCA-4 ADC portable Infra Red Gas Analyser (IRGA) manufactured by Analytical Development Company in Hoddeson, England. The leaf cuvettes of the IRGA were initially secured on the upper surface of the leaf, with the PAR sensor facing sunlight upwards. Subsequently, the cuvettes were adjusted to optimize PAR exposure and minimize the difference in CO_2 and water vapor readings between the reference and analytical cells. Once stability was achieved, the exchange switch was activated, and the values were recorded.

2.3.5. Number of grains/ spike

The threshed grains from spikes were counted to obtain grain number/spike.

2.3.6 .Grain weight/ spike

The weight of total grains per spike from three spikes in each replication from each site was taken in grams & average was recorded.

2.3.7. Grain yield

The weight of total grains per plant from three plants in each replication from each site was taken in grams & average was recorded.

2.3.8. Biological yield

The biological yield was calculated in grams for three plants per replication from each site and average was calculated.

2.4. Statistical analysis

Soil data were analyzed using an independent samples *t*-test at a significance level of **$P < 0.05$**. Physiological and yield parameters of wheat were analyzed using **factorial analysis of variance (ANOVA)** with **sampling site, burning condition, and growth stage** as fixed factors. Following ANOVA, the **Site × Burning × Growth Stage interaction means** were compared using **Tukey's Honestly Significant Difference (HSD) test** at **$P < 0.05$**. Values presented in the graphs are expressed as **mean ± standard error (SE)**. Bars labeled with different lowercase letters indicate statistically significant differences among the **Site × Burning × Growth Stage interaction means** according to Tukey's HSD test (**$P < 0.05$**)

3. RESULTS

3.1. Soil Physicochemical Parameters

The physicochemical properties of pre- and post-burning soils are presented in Table 1 to provide the soil conditions associated with the physiological responses observed in wheat. Independent-samples t-tests indicated significant differences ($P < 0.05$) between pre- and post-burning soils for all measured parameters.

Table 1: Physicochemical properties of pre- and post-burning soil samples (mean ± SE, n = 9).

Parameter	Pre-Burning	Post-Burning
Total Nitrogen (mg/kg)	625.2 ± 23.09	516.8 ± 17.09*
Total Phosphorus (mg/kg)	601.0 ± 16.93	518.3 ± 25.09*
Total Potassium (mg/kg)	172.5 ± 8.99	208.8 ± 8.38*
Organic Matter (mg/kg)	29313.9 ± 653.62	27332.2 ± 695.81*
EC (dS/m)	0.9 ± 0.10	1.9 ± 0.16*

pH	7.5 ± 0.20	8.1 ± 0.36*

Values are presented as mean ± SE (n = 9). Asterisks (*) indicate significant differences between pre- and post-burning soils based on an independent-samples t-test (P < 0.05). Organic matter was calculated from organic carbon determined by the Walkley and Black method using a conversion factor of 1.724.

3.2. Physiological parameters of Wheat

3.2.1. Relative water content

The relative water content (RWC) of wheat grown in post-burning soil decreased at both the vegetative and heading stages across all sampling sites compared with the corresponding pre-burning conditions (Figure 2). Before burning, RWC ranged from 78.3 to 85.7% at the vegetative stage and from 79.0 to 83.5% at the heading stage. Following burning, RWC declined to 68.7–76.8% and 66.7–71.3% at the vegetative and heading stages, respectively. The greatest decrease in RWC was observed at Site 7 (Bithmara), amounting to 16.9% at the vegetative stage and 17.6% at the heading stage, whereas the smallest decrease was recorded at Site 1 (Khardwal), with reductions of 8.9% and 11.6% at the respective stages.

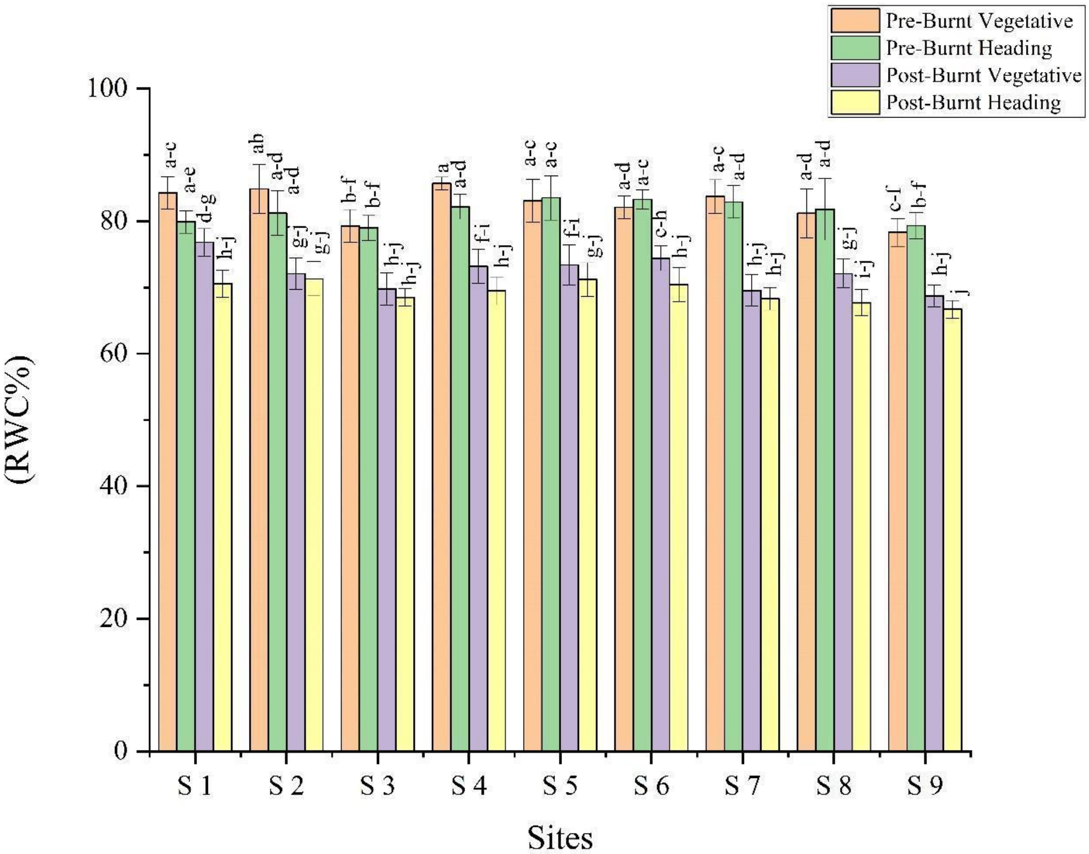

Figure 2: Changes in relative water content of wheat grown in pre and post-burnt soil **(Values are presented as mean ± SE (n = 3). Bars with different lowercase letters indicate significant differences among the Site × Burning × Growth Stage interaction means according to Tukey's HSD test (P < 0.05))**

3.2.2. Chlorophyll content

Chlorophyll content (SPAD units) in wheat grown in post-burning soil decreased at both the vegetative and heading stages across all sampling sites compared with the corresponding pre-burning conditions (Figure 3). Before burning, chlorophyll content ranged from 52.67 to 56.47 SPAD units at the vegetative stage and from 47.54 to 51.93 SPAD units at the heading stage. Following burning, chlorophyll content declined to 43.67–47.56 and 38.12–42.25 SPAD units at the vegetative and heading stages, respectively. The greatest reduction in chlorophyll content was observed at Site 9 (Bithmara) during the vegetative stage (19.44%) and at Site 7 (Bithmara) during the heading stage (21.60%), whereas the smallest reduction at both the vegetative (13.48%) and heading (12.58%) stages was recorded at Site 3 (Khardwal) compared with the corresponding pre-burning conditions.

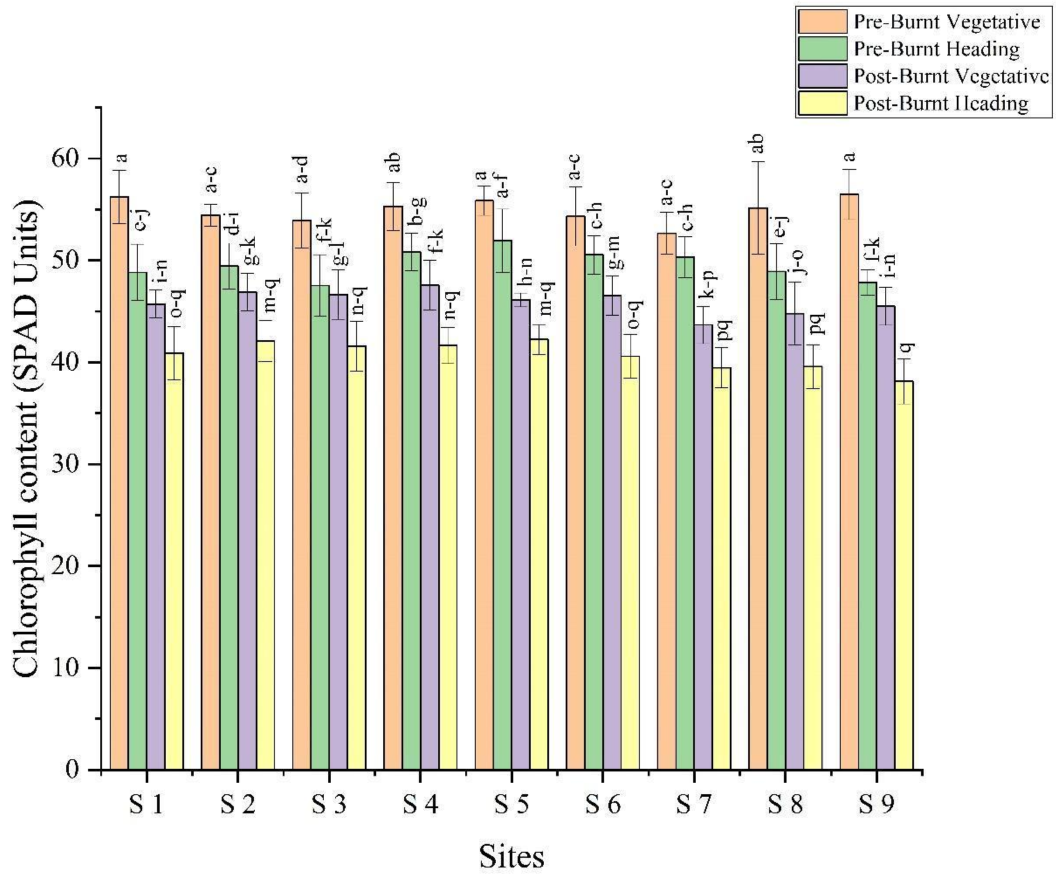

Figure 3: Changes in chlorophyll content of wheat grown in pre and post-burnt soil **(Values are presented as mean ± SE (n = 3). Bars with different lowercase letters indicate significant differences among the Site × Burning × Growth Stage interaction means according to Tukey's HSD test (P < 0.05))**

3.2.3. Chlorophyll fluorescence

Chlorophyll fluorescence (Fv/Fm) of wheat grown in post-burning soil decreased at both the vegetative and heading stages across all sampling sites compared with the corresponding pre-burning conditions (Figure 4). Before burning, Fv/Fm values ranged from 0.675 to 0.709 at the vegetative stage and from 0.592 to 0.684 at the heading stage. Following burning, Fv/Fm declined to 0.583–0.638 and 0.492–0.603 at the vegetative and heading stages, respectively. The greatest reduction in chlorophyll fluorescence was observed at Site 7 (Bithmara) during the vegetative stage (15.75%) and at Site 9 (Bithmara) during the heading stage (17.73%), whereas the smallest reduction was recorded at Site 3 (Khardwal) during the vegetative stage (9.77%) and at Site 1 (Khardwal) during the heading stage (11.80%) compared with the corresponding pre-burning conditions.

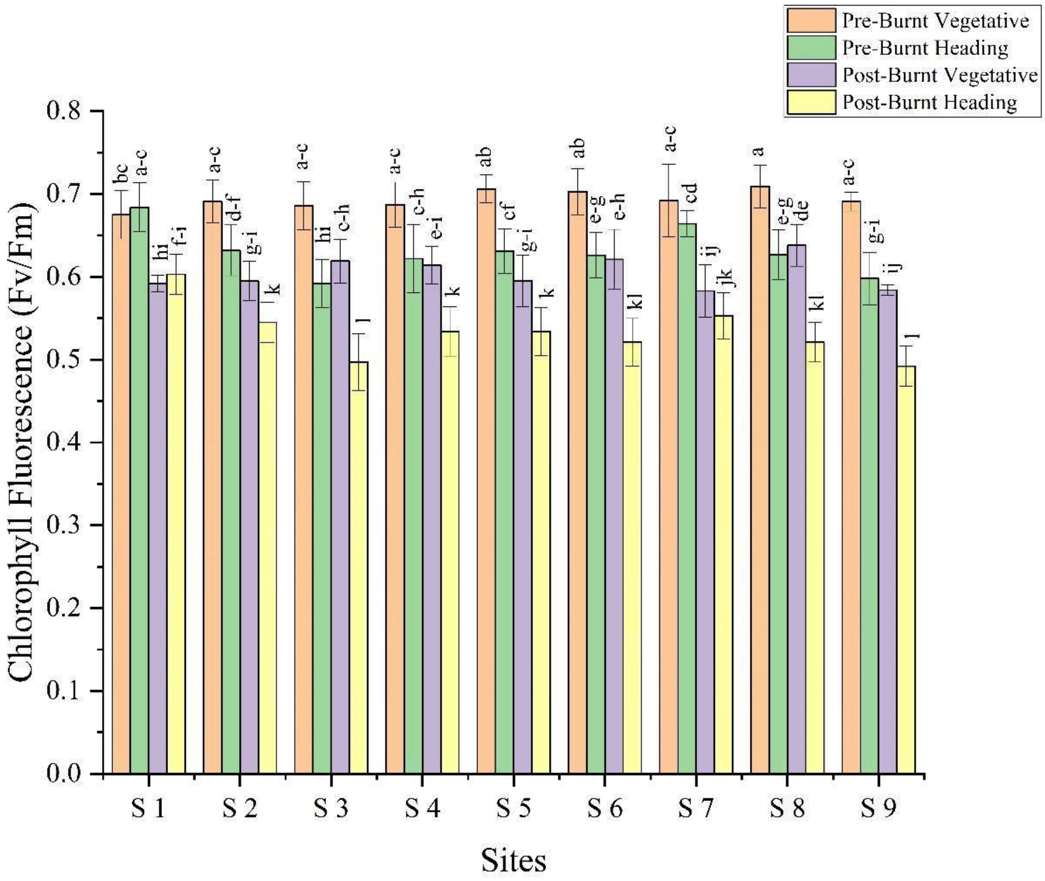

Figure 4: Changes in chlorophyll fluorescence of wheat grown in pre and post-burnt soil **(Values are presented as mean ± SE (n = 3). Bars with different lowercase letters indicate significant differences among the Site × Burning × Growth Stage interaction means according to Tukey's HSD test (P < 0.05))**

3.2.4. Photosynthetic rate

The photosynthetic rate of wheat grown in post-burning soil decreased at both the vegetative and heading stages across all sampling sites compared with the corresponding pre-burning conditions (Figure 5). Before burning, the photosynthetic rate ranged from 10.33 to 15.54 µmol CO_2 m^{-2} s^{-1} at the vegetative stage and from 10.12 to 13.78 µmol CO_2 m^{-2} s^{-1} at the heading stage. Following burning, the photosynthetic rate declined to 9.11–11.78 and 7.89–10.21 µmol CO_2 m^{-2} s^{-1} at the vegetative and heading stages, respectively. The greatest reduction in the photosynthetic rate was observed at Site 4 (Samain) during the vegetative stage (24.20%) and at Site 8 (Bithmara) during the heading stage (31.74%), whereas the smallest reduction was recorded at Site 3 (Khardwal) during both the vegetative (7.86%)

and heading (12.10%) stages compared with the corresponding pre-burning conditions.

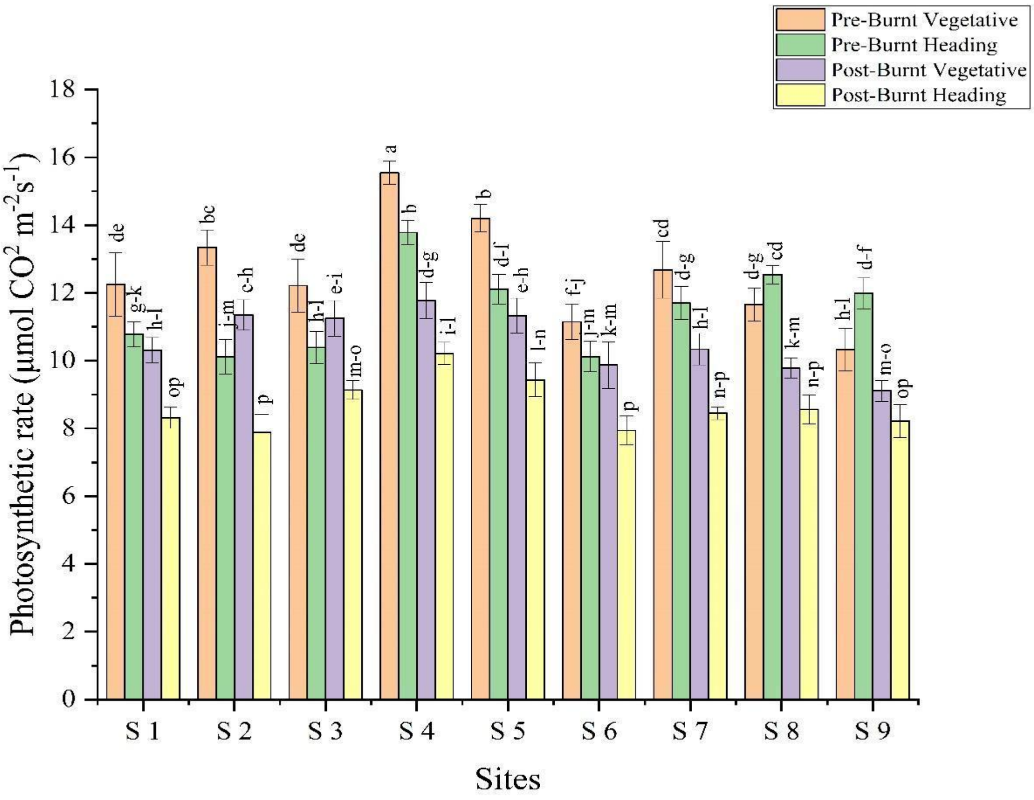

Figure 5: Changes in photosynthetic rate of wheat grown in pre and post-burnt soil **(Values are presented as mean ± SE (n = 3). Bars with different lowercase letters indicate significant differences among the Site × Burning × Growth Stage interaction means according to Tukey's HSD test (P < 0.05))**

3.2.5. Transpiration rate

The transpiration rate of wheat grown in post-burning soil decreased at both the vegetative and heading stages across all sampling sites compared with the corresponding pre-burning conditions (Figure 6). Before burning, the transpiration rate ranged from 5.25 to 7.21 mmol H_2O m^{-2} s^{-1} at the vegetative stage and from 4.89 to 6.34 mmol H_2O m^{-2} s^{-1} at the heading stage. Following burning, the transpiration rate declined to 4.54–5.53 and 3.89–5.11 mmol H_2O m^{-2} s^{-1} at the vegetative and heading stages, respectively. The greatest reduction in transpiration rate was observed at Site 4 (Samain) during the vegetative stage (27.46%) and at Site 7 (Bithmara) during the heading stage (33.20%), whereas the smallest reduction was recorded at Site 1 (Khardwal) during the vegetative stage (9.93%) and at Site 2 (Khardwal) during the heading stage (13.50%) compared with the corresponding pre-burning conditions.

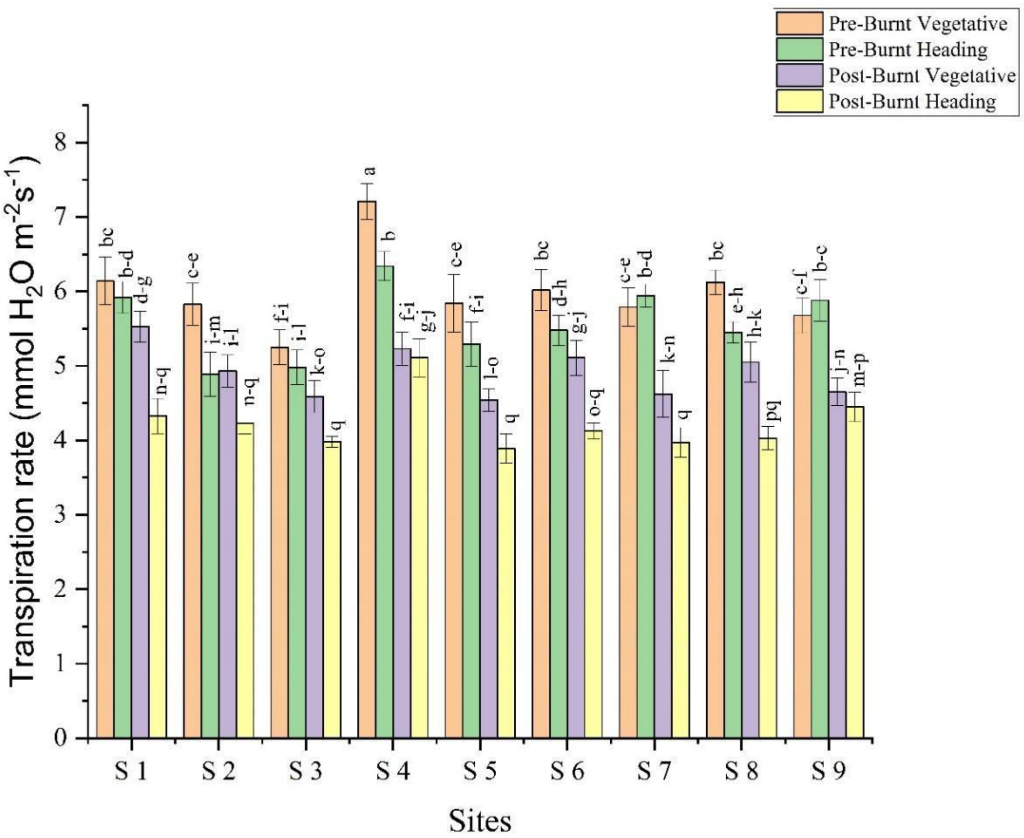

Figure 6: Changes in transpiration rate of wheat grown in pre and post-burnt soil **(Values are presented as mean ± SE (n = 3). Bars with different lowercase letters indicate significant differences among the Site × Burning × Growth Stage interaction means according to Tukey's HSD test (P < 0.05))**

3.2.6. Stomatal conductance

Stomatal conductance of wheat grown in post-burning soil decreased at both the vegetative and heading stages across all sampling sites compared with the corresponding pre-burning conditions (Figure 7). Before burning, stomatal conductance ranged from 0.378 to 0.417 mol H_2O m^{-2} s^{-1} at the vegetative stage and from 0.355 to 0.413 mol H_2O m^{-2} s^{-1} at the heading stage. Following burning, stomatal conductance declined to 0.289–0.321 and 0.264–0.307 mol H_2O m^{-2} s^{-1} at the vegetative and heading stages, respectively. The greatest reduction in stomatal conductance was observed at Site 7 (Bithmara) during the vegetative stage (29.85%) and at Site 8 (Bithmara) during the heading stage (36.08%), whereas the smallest reduction was recorded at Site 1 (Khardwal) during the vegetative stage (18.62%) and at Site 3 (Khardwal) during the heading stage (16.58%) compared with the corresponding pre-burning conditions.

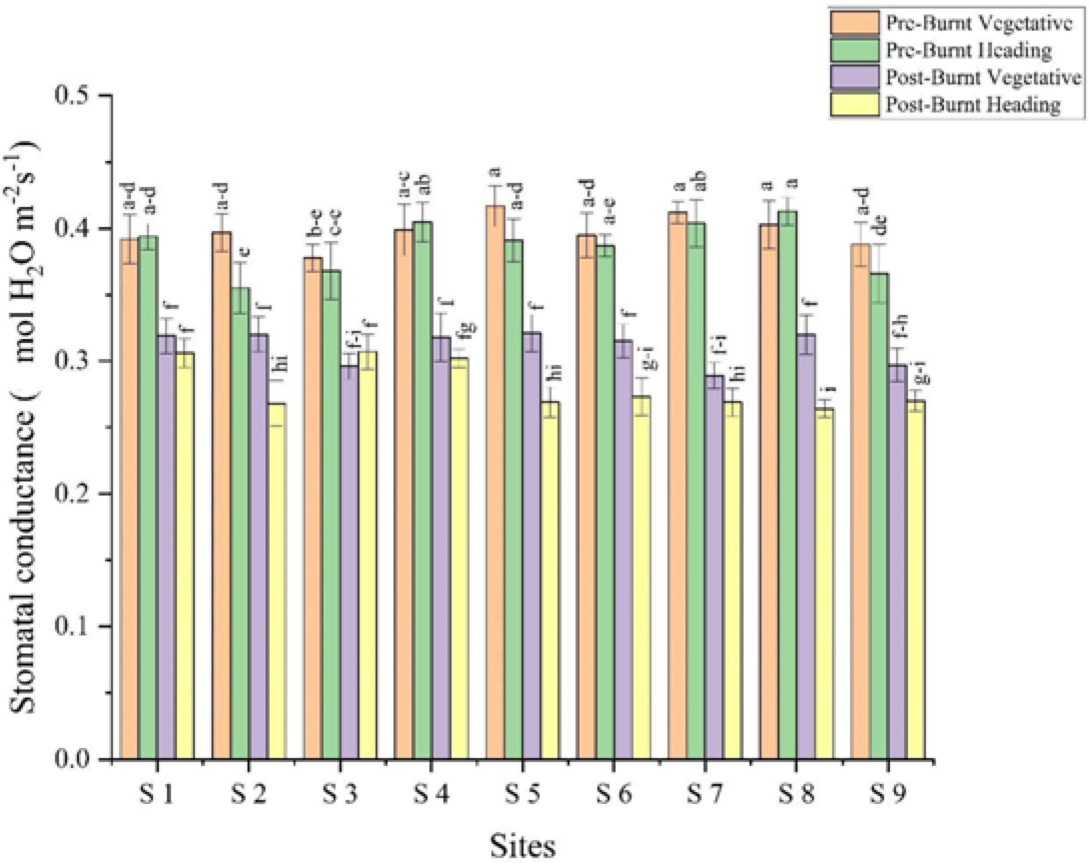

Figure 7: Changes in stomatal conductance of wheat grown in pre and post-burnt soil **(Values are presented as mean ± SE (n = 3). Bars with different lowercase letters indicate significant differences among the Site × Burning × Growth Stage interaction means according to Tukey's HSD test (P < 0.05))**

3.2.7. Yield and yield attributes

3.2.7.1. Grain weight per spike and number of grains per spike

The grain weight per spike of wheat grown in post-burning soil decreased across all sampling sites compared with the corresponding pre-burning conditions (Figure 8). Before burning, grain weight per spike ranged from 1.98 to 2.31 g, whereas after burning it declined to 1.57–1.91 g. The greatest reduction in grain weight per spike was observed at Site 8 (Bithmara) (29.0%), while the smallest reduction was recorded at Site 2 (Khardwal) (9.6%) compared with the corresponding pre-burning conditions. The number of grains per spike of wheat grown in post-burning soil decreased across all sampling sites compared with the corresponding pre-burning conditions (Figure 9). Before burning, the number of grains per spike ranged from 48 to 57, whereas after burning it declined to 42–51. The greatest reduction in the number of grains per spike was observed at Site 8 (Bithmara) (26.3%), while the smallest reduction was recorded at Site 2 (Khardwal) (4.2%) compared with the corresponding pre-burning conditions.

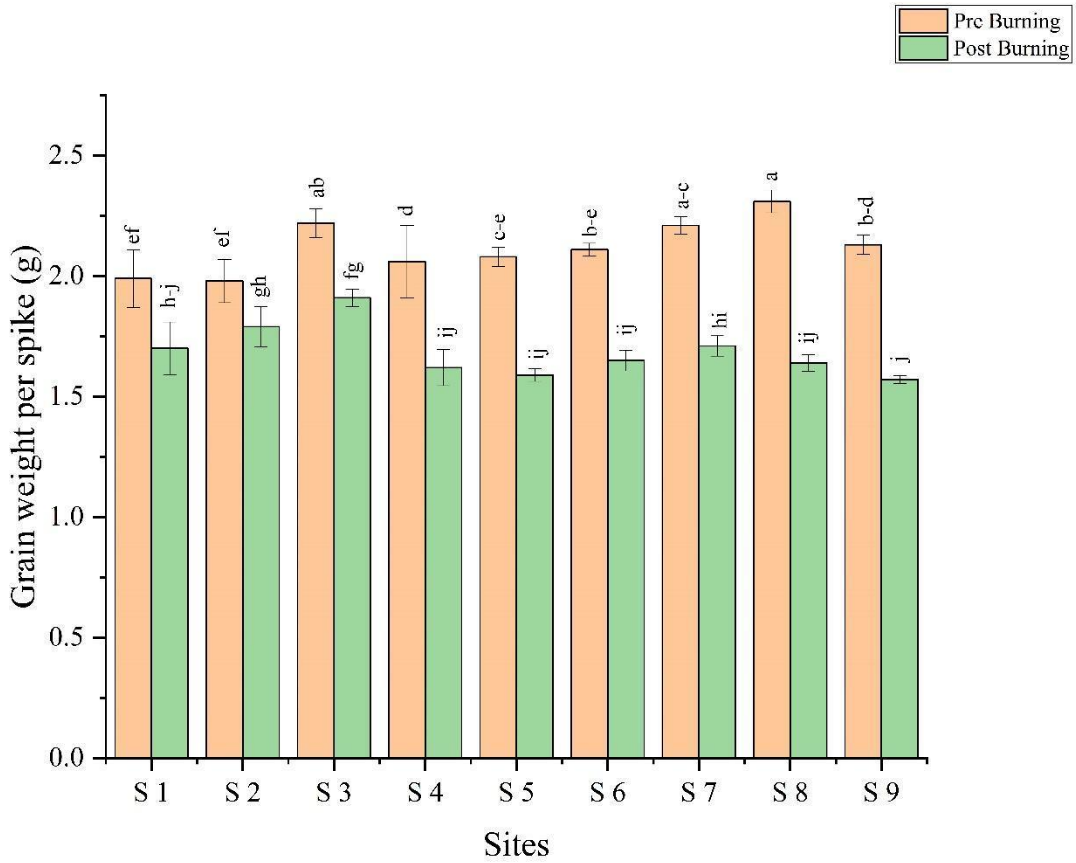

Figure 8: Changes in grain weight per spike of wheat grown in pre and post-burnt soil **(Values are presented as mean ± SE (n = 3). Bars with different lowercase letters indicate significant differences among the Site × Burning × Growth Stage interaction means according to Tukey's HSD test (P < 0.05))**

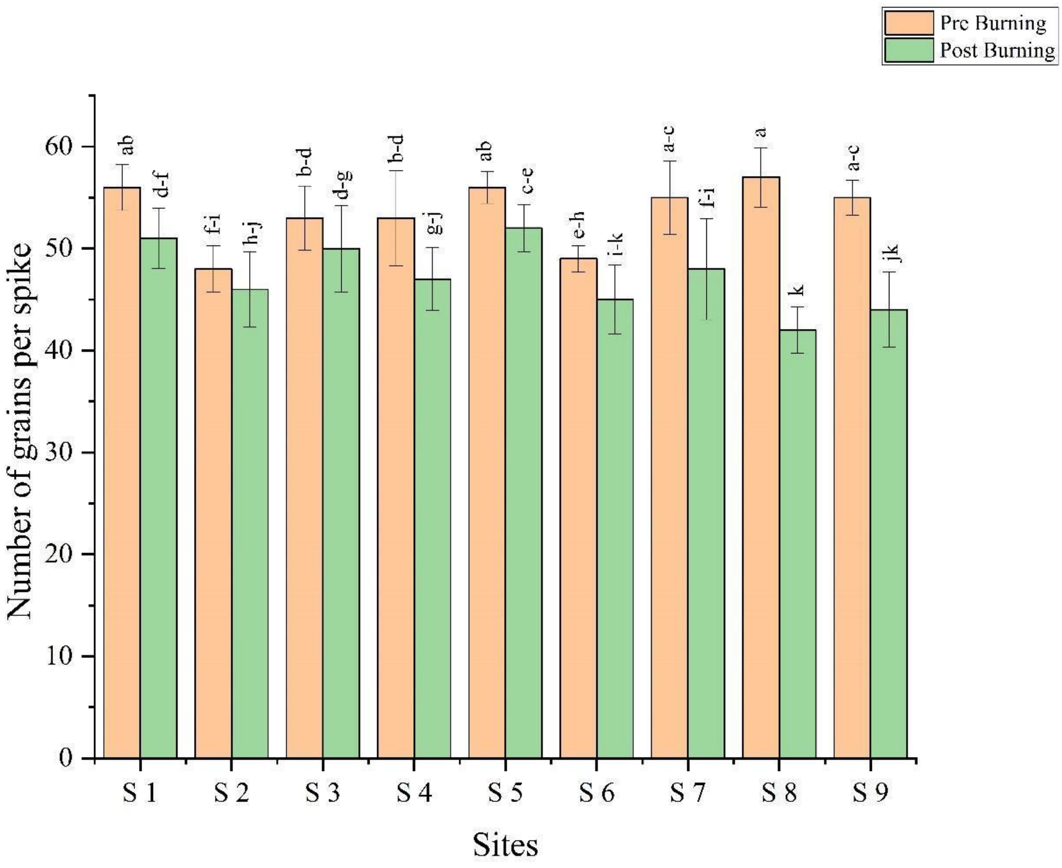

Figure 9: Changes in number of grains per spike of wheat grown in pre and post-burnt soil **(Values are presented as mean ± SE (n = 3). Bars with different lowercase letters indicate significant differences among the Site × Burning × Growth Stage interaction means according to Tukey's HSD test (P < 0.05))**

3.2.7.2. Grain yield and biological yield

The grain yield of wheat grown in post-burning soil decreased across all sampling sites compared with the corresponding pre-burning conditions (Figure 10). Before burning, grain yield ranged from 3.8 to 5.2 g plant^{-1}, whereas after burning it declined to 3.5–4.1 g plant^{-1}. The greatest reduction in grain yield was observed at Site 8 (Bithmara) (24.5%), while the smallest reduction was recorded at Site 3 (Khardwal) (2.6%) compared with the corresponding pre-burning conditions. The biological yield of wheat grown in post-burning soil decreased across all sampling sites compared with the corresponding pre-burning conditions (Figure 11). Before burning, biological yield ranged from 10.37 to 13.52 g plant^{-1}, whereas after burning it declined to 9.34–11.32 g plant^{-1}. The greatest reduction in biological yield was observed at Site 9 (Bithmara) (28.0%), while the smallest reduction was recorded at Site 1 (Khardwal) (9.2%) compared with the corresponding pre-burning conditions.

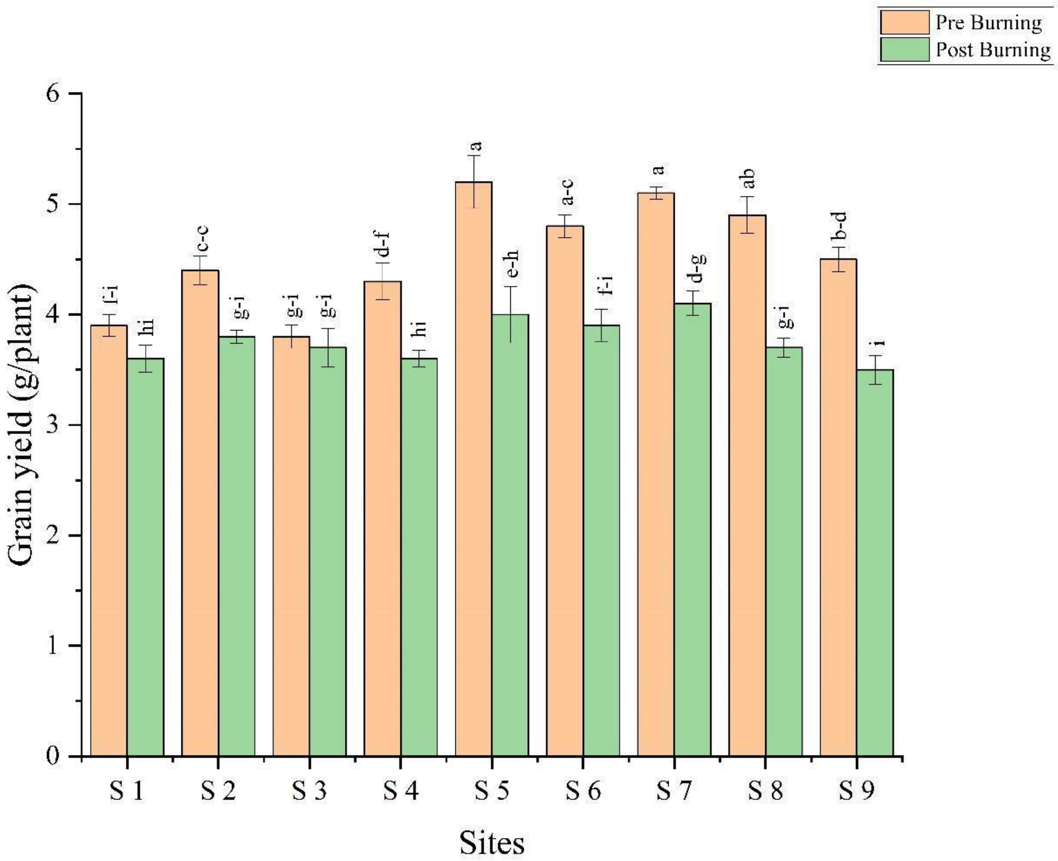

Figure 10: Changes in grain yield of wheat grown in pre and post-burnt soil **(Values are presented as mean ± SE (n = 3). Bars with different lowercase letters indicate significant differences among the Site × Burning × Growth Stage interaction means according to Tukey's HSD test (P < 0.05))**

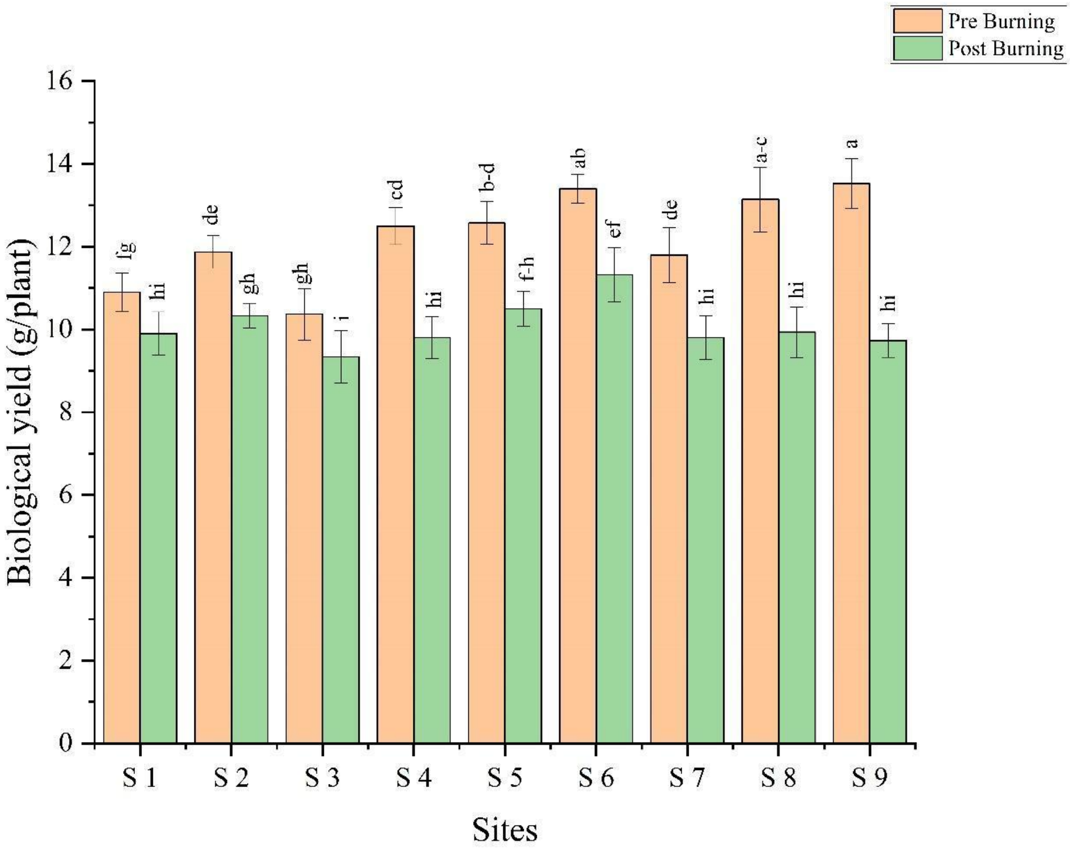

Figure 11: Changes in biological yield of wheat grown in pre and post-burnt soil **(Values are presented as mean ± SE (n = 3). Bars with different lowercase letters indicate significant differences among the Site × Burning × Growth Stage interaction means according to Tukey's HSD test (P < 0.05))**

4. DISCUSSION

Rice residue burning alters soil physicochemical properties and nutrient availability, which may collectively impose abiotic stress on subsequent crops. The observed changes in soil pH, electrical conductivity, organic matter and nutrient status may have influenced plant water relations and physiological performance. Previous studies have suggested that changes in soil physical conditions following residue burning may contribute to temporary waterlogging, hypoxia and oxidative stress under certain environmental conditions; however, these processes were not directly measured in the present study and are therefore discussed only as possible mechanisms rather than demonstrated causes. In wheat farming, considerable crop losses due to waterlogging are estimated at 15–20% annually (Katerova *et al.* 2021). The effects of waterlogging are observed in alterations to plant processes like photosynthesis, respiration, transpiration, and antioxidative mechanisms. **Moreover, the increased soil electrical conductivity observed after burning may have contributed to osmotic imbalance and reduced water uptake by plants, thereby affecting plant water status.** As a result, crop growth and productivity could suffer adverse effects. Therefore, rice residue burning may influence soil properties, as well as the physiology and yield of subsequent wheat crops.

RWC is considered a gauge of plant water status, showcasing the metabolic activity of the plant system and serving as an indicator of dehydration in many plants (Anjum *et al.* 2017; Quemada *et al.* 2021). It closely correlates with the physiological functions of plants and is frequently employed to demonstrate the correlation between plant leaves and water content. RWC also signifies the capacity to maintain water content and the degree of leaf wilting. The current investigation revealed a reduction in the relative water content of wheat grown in soil post-burning during both the vegetative and heading stages compared to pre-burning conditions. This decline in RWC aligns with findings from Agnes *et al*. (2009), where notably decreased RWC values were observed even at anthesis in two susceptible wheat cultivars, suggesting a correlation with drought stress.

Chlorophyll, found predominantly in chloroplasts, serves as a primary site for photosynthesis and is closely linked to the photosynthetic rate and the greenness of flag leaves (Wang and Grim, 2021). Alterations in chlorophyll levels serve as indicators of the tolerance or susceptibility of genotypes to harsh environmental conditions such as intense light, high temperatures, and dry air, particularly in cultivars sown at different times (Mishra *et al.* 2017). In this study, a decrease in chlorophyll content (measured in SPAD units) was observed at both stages under post-burning conditions compared to the pre-burning. **The decline in chlorophyll levels suggests impaired photosynthetic function, which may be associated with altered soil physicochemical conditions, reduced nutrient availability and reduced stomatal conductance following burning. The reduction in chlorophyll content and quantum yield under stress conditions may reflect impairment of the photosynthetic apparatus associated with altered soil conditions following burning. Multiple studies have reported similar reductions in chlorophyll under waterlogging stress, suggesting a possible physiological response under comparable abiotic stress conditions.** During the emergence stage, a 10-day period of stress resulted in chlorophyll reductions ranging from 15% to 33% across four wheat genotypes (Yadav *et al.* 2015). Similarly, at the tillering stage, reductions ranging from 41% to 61% were observed in six wheat varieties after 28 days of waterlogging (Amri *et al.* 2014). Zheng *et al*. (2009) reported that in wheat cultivars, chlorophyll content in the flag leaf was significantly lower under waterlogging and salt stress treatments compared to control plants at 18 days after anthesis (DAA). The chlorophyll fluorescence (Fv/Fm ratio) indicates the photosystem II's (PS II) electron trapping ability, with reductions linked to D1 reaction-center protein damage in PS II (Fatma *et al.* 2021). This parameter is widely used to assess photosynthetic activity and its underlying mechanisms, particularly under various abiotic and biotic stresses, providing intricate insights into plant physiology. In our recent study, we observed a decrease in chlorophyll fluorescence during both vegetative and heading stages under post-burning conditions compared to pre-burning conditions. This reduction could be attributed to decreased relative water content (RWC), chlorophyll content and chlorophyll stability index after burning. Similar findings were evident in chickpea, where drought stress led to a significant reduction in the quantum yield of photosystem II (Fv/Fm), which was positively correlated with RWC (Kumar *et al.* 2018). **In wheat, reductions in the Fv/Fm ratio have also been reported under waterlogging stress** (Amri *et al.* 2014; Wu *et al.* 2015; Herzog *et al.* 2016) **indicating that similar physiological responses may occur under different abiotic stresses.** This leads to a diminished efficacy in utilizing captured photon energy (Shao *et al.* 2013).

In the present investigations, the photosynthetic rate of wheat grown in soil affected by post-burning practices decreased during both the vegetative and heading stages compared to conditions before burning. The decline in photosynthesis could be attributed to alterations in soil physicochemical properties and nutrient depletion caused by post-burning conditions. **The observed decline in photosynthesis may involve both stomatal and non-stomatal limitations associated with the altered soil conditions following burning.** Non-stomatal factors, including reduced chlorophyll stability index and ion uptake affecting enzymatic reactions, contribute to this decline. **The reductions in osmotic potential (Ψs), RWC and stomatal conductance observed in the present study suggest that partial stomatal limitation may have contributed to the reduced photosynthetic rate.** This finding aligns with similar results observed by Bashir *et al*. (2020) in pea plants and Ahmad *et al*. (2018) in wheat crops. **Similar reductions in photosynthetic rate and stomatal conductance have been reported under various abiotic stresses, including waterlogging and salinity (Zheng *et al.* 2009).** The study findings indicate a decline in wheat transpiration rate after soil post-burning, evident during both vegetative and heading stages compared to pre-burning conditions. **This reduction may be associated with the observed decreases in osmotic potential, relative water content (RWC), and stomatal conductance under post-**

burning conditions. Stomatal conductance plays a pivotal role in regulating transpiration, and its reduction due to various stress factors can lead to decreased water loss through stomata. Additionally, the decrease in transpiration rate may relate to stomatal pore size regulation, as discussed by Beltrano *et al*. (2006). Similar results were reported by Zhao *et al*. (2020) as transpiration rate decreased significantly in winter wheat under moderate and severe water stress. Stomatal closure is an immediate response to prevent excessive water loss via transpiration. Our study reveals a decrease in stomatal conductance at both vegetative and heading stages after burning, compared to pre-burning conditions. **This reduction could be associated with the observed decreases in osmotic potential and relative water content under post-burning conditions.** This phenomenon aligns with previous findings by Baroowa *et al*. (2015) in mungbeans, Ahmad *et al*. (2018) in wheat, and Bashir *et al*. (2020) in pea plants under soil moisture stress.

Plants' reaction to water stress is influenced by various factors including developmental stage, stress severity and duration, and genetic characteristics of the cultivar (Seleiman et al. 2021). Grain crop yield encompasses two primary components: grain number and grain weight, which are typically determined at different stages of the wheat crop cycle (Brinton and Uauy, 2019). Following burning, there was a notable decrease in wheat yield and its associated attributes compared to pre-burning conditions. The decline in various yield-related traits in wheat under post-burning conditions may stem from the adverse effects on physiological-biochemical characteristics and dry matter accumulation. Specifically, the number of grains per spike and biological yield in wheat were negatively impacted, leading to a decrease in grain yield per plant. **The observed nutrient depletion together with alterations in soil physicochemical properties following burning may have reduced photosynthesis and assimilate translocation, thereby contributing to lower yield potential**. **The altered soil conditions following burning were associated with lower seed and biological yields**, possibly due to the challenging growing environment, supported by decreased plant water status and growth parameters in wheat. The stress induced by insufficient water uptake from the soil accelerates crop maturation and constrains the development and expansion of leaves, both critical for plant survival, and jeopardizing the overall economic output (Chauhan and Williams, 2018). Ding *et al*. (2020) observed a 9 to 15% decline in wheat yield when waterlogging occurred during the seedling, jointing, and tillering stages. Wheat is notably vulnerable to waterlogging, commonly resulting in reduced grain yield per plant. Extensive research, including studies by Olgun *et al*. (2008), Pampana *et al*. (2016), and Ploschuk *et al*. (2018), has documented substantial grain yield reductions ranging from 50% to 70% due to prolonged waterlogging during sowing, seedling emergence, flowering, and grain-filling stages, attributed to impaired seed set and fewer spikes per unit area.

5. CONCLUSION AND FUTURE PROSPECTIVE

The present study demonstrated that wheat grown in post-burning rice-field soils under screen-house pot conditions exhibited significant reductions in physiological performance and productivity compared with wheat grown in pre-burning soils. Reductions in photosynthetic rate, transpiration rate, and stomatal conductance indicated physiological stress associated with soil changes following rice residue burning. These physiological responses were accompanied by decreases in grain yield and biological yield, suggesting that alterations in soil properties after burning adversely affected the performance of the succeeding wheat crop under the experimental conditions. Overall, the findings highlight the soil-mediated effects of rice residue burning on wheat physiology and productivity and emphasize the importance of sustainable residue management practices, such as baling, mulching, and composting, to maintain soil quality and support sustainable crop production. Further field-based investigations are required to determine the extent to which these findings apply to field-scale wheat productivity under diverse agroecological conditions.

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REFERENCES

1. Abdurrahman, M.I., Chaki, S. and Saini, G., 2020. Stubble burning: Effects on health and environment, regulations and management practices. *Environmental Advances*, 2, p.100011. https://doi.org/10.1016/j.envadv.2020.100011
2. Agnes, G., Jolan, C., Maria, S., Adrienn, G., Laszlo, C., Irma, T., Janos, G. and Laszlo, E., 2009. Glutathione transferase activity and expression patterns during grain filling in flag leaves of wheat genotypes differing in drought tolerance: Response to water deficit. *Journal of Plant Physiology*, 166, pp.1878–1891. https://doi.org/10.1016/j.jplph.2009.06.004
3. Ahmad, Z., Waraich, E.A., Akhtar, S., Anjum, S., Ahmad, T., Mahboob, W. and Rizwan, M., 2018. Physiological responses of wheat to drought stress and its mitigation approaches. *Acta Physiologiae Plantarum*, 40(4), pp.1–13. https://doi.org/10.1007/s11738-018-2651-6
4. Amri, M., El Ouni, M.H. and Salem, M.B., 2014. Waterlogging affects the development, yield and components, chlorophyll content and chlorophyll fluorescence of six bread wheat genotypes (*Triticum aestivum* L.). *Bulgarian Journal of Agricultural Science*, 20(3), pp.647–657.
5. Anjum, S.A., Ashraf, U., Tanveer, M., Khan, I., Hussain, S., Shahzad, B. and Wang, L.C., 2017. Drought induced changes in growth, osmolyte accumulation and antioxidant metabolism of three maize hybrids. *Frontiers in Plant Science*, 8, p.69. https://doi.org/10.3389/fpls.2017.00069
6. Baroowa, B., Gogoi, N., Paul, S. and Baruah, K.K., 2015. Response of leaf water status, stomatal characteristics, photosynthesis and yield in black gram and green gram genotypes to soil water deficit. *Functional Plant Biology*, 42(10), pp.1010–1018. https://doi.org/10.1071/FP15064
7. Barrs, H.D. and Weatherley, P.E., 1962. A re-examination of the relative turgidity technique for estimating water deficits in leaves. *Australian Journal of Biological Sciences*, 15(3), pp.413–428. https://doi.org/10.1071/BI9620413
8. Bashir, T., Naz, S. and Bano, A., 2020. Plant growth promoting rhizobacteria in combination with plant growth regulators attenuate the effect of drought stress. *Pakistan Journal of Botany*, 52(3), pp.783–792. https://doi.org/10.30848/PJB2020-3(5)
9. Beltrano, J., Ronco, M.G. and Arango, M.C., 2006. Soil drying and rewatering applied at three grain developmental stages affect differentially growth and grain protein deposition in wheat (*Triticum aestivum* L.). *Brazilian Journal of Plant Physiology*, 18, pp.341–350. https://doi.org/10.1590/S1677-04202006000200012
10. Bhuvaneshwari, S., Hettiarachchi, H. and Meegoda, J.N., 2019. Crop residue burning in India: Policy challenges and potential solutions. *International Journal of Environmental Research and Public Health*, 16(5), p.832. https://doi.org/10.3390/ijerph16050832
11. Bremner, J.M. and Mulvaney, C.S., 1983. Nitrogen-total. In: A.L. Page, ed. *Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties*. Madison: American Society of Agronomy, pp.595–624. https://doi.org/10.2134/agronmonogr9.2.2ed.c31
12. Brinton, J. and Uauy, C., 2019. A reductionist approach to dissecting grain weight and yield in wheat. *Journal of Integrative Plant Biology*, 61(3), pp.337–358. https://doi.org/10.1111/jipb.12741
13. Chataut, G., Bhatta, B., Joshi, D., Subedi, K. and Kafle, K., 2023. Greenhouse gases emission from agricultural soil: A review. *Journal of Agriculture and Food Research*, 11, p.100533. https://doi.org/10.1016/j.jafr.2022.100533
14. Chauhan, Y.S. and Williams, R., 2018. Physiological and agronomic strategies to increase mungbean yield in climatically variable environments of Northern Australia. *Agronomy*, 8(6), p.83. https://doi.org/10.3390/agronomy8060083
15. Chawala, P. and Sandhu, H.A.S., 2020. Stubble-burn area estimation and its impact on ambient air quality of Patiala and Ludhiana district, Punjab, India. *Heliyon*, 6(1), p.e03095. https://doi.org/10.1016/j.heliyon.2019.e03095
16. Ding, J., Liang, P., Wu, P., Zhu, M., Li, C., Zhu, X. and Guo, W., 2020. Effects of waterlogging on grain yield and associated traits of historic wheat cultivars in the middle and lower reaches of the Yangtze River, China. *Field Crops Research*, 246, p.107695. https://doi.org/10.1016/j.fcr.2019.107695

17. Dutta, A., Patra, A., Hazra, K.K., Nath, C.P., Kumar, N. and Rakshit, A., 2022. A state of the art review in crop residue burning in India: Previous knowledge, present circumstances and future strategies. *Environmental Challenges*, 8, p.100581. https://doi.org/10.1016/j.envc.2022.100581
18. El-Sobky, E.S.E., 2017. Effect of burned rice straw, phosphorus and nitrogen fertilization on wheat (*Triticum aestivum* L.). *Annals of Agricultural Sciences*, 62(1), pp.113–120. https://doi.org/10.1016/j.aoas.2017.05.003
19. Fatma, M., Iqbal, N., Sehar, Z., Alyemeni, M.N., Kaushik, P., Khan, N.A. and Ahmad, P., 2021. Methyl jasmonate protects the PS II system by maintaining the stability of chloroplast D1 protein and accelerating enzymatic antioxidants in heat-stressed wheat plants. *Antioxidants*, 10(8), p.1216. https://doi.org/10.3390/antiox10081216
20. Gupta, P.K., Sahai, S., Singh, N., Dixit, C.K., Singh, D.P., Sharma, C. and Garg, S.C., 2004. Residue burning in rice–wheat cropping system: Causes and implications. *Current Science*, 87, pp.1713–1717.
21. Herzog, M., Striker, G.G., Colmer, T.D. and Pedersen, O., 2016. Mechanisms of waterlogging tolerance in wheat – a review of root and shoot physiology. *Plant, Cell and Environment*, 39(5), pp.1068–1086. https://doi.org/10.1111/pce.12676
22. Jain, N., Bhatia, A. and Pathak, H., 2014. Emission of air pollutants from crop residue burning in India. *Aerosol and Air Quality Research*, 14(1), pp.422–430. https://doi.org/10.4209/aaqr.2013.01.0031
23. Katerova, Z., Sergiev, I., Todorova, D., Shopova, E., Dimitrova, L. and Brankova, L., 2021. Physiological responses of wheat seedlings to soil waterlogging applied after treatment with selective herbicide. *Plants*, 10(6), p.1195. https://doi.org/10.3390/plants10061195
24. Kaur, M., Malik, D.P., Malhi, G.S., Sardana, V., Bolan, N.S., Lal, R. and Siddique, K.H., 2022. Rice residue management in the Indo-Gangetic Plains for climate and food security: A review. *Agronomy for Sustainable Development*, 42(5), p.92. https://doi.org/10.1007/s13593-022-00826-3
25. Krishna, K.L. and Meenakshi, J.V., 2022. Agricultural productivity growth and structural transformation in rural India: Some recent evidence. *Journal of Quantitative Economics*, 20(Suppl 1), pp.277–302. https://doi.org/10.1007/s40953-022-00309-3
26. Kumar, P., Boora, K.S., Kumar, N., Batra, R., Goyal, M., Sharma, K.D. and Yadav, R.C., 2018. Traits of significance for screening of chickpea (Cicer arietinum L.) genotypes under terminal drought stress. Journal of Agrometeorology, 20(1), pp.40–45. https://doi.org/10.54386/jam.v20i1.94
27. Kumar, P., Kumar, S. and Joshi, L., 2015. Socioeconomic and Environmental Implications of Agricultural Residue Burning: A Case Study of Punjab, India. Cham: Springer Nature. https://doi.org/10.1007/978-81-322-2014-5
28. Lopes, A.A., Tasneem, D. and Viriyavipart, A., 2023. Determinants of wheat residue burning: Evidence from India. PLoS ONE, 18(12), p.e0296059. https://doi.org/10.1371/journal.pone.0296059
29. Mishra, D., Shekhar, S., Agrawal, L., Chakraborty, S. and Chakraborty, N., 2017. Cultivar-specific high temperature stress responses in bread wheat (Triticum aestivum L.) associated with physicochemical traits and defense pathways. Food Chemistry, 221, pp.1077–1087. https://doi.org/10.1016/j.foodchem.2016.11.114
30. Olgun, M., Kumlay, A.M., Adiguzel, M.C. and Caglar, A., 2008. The effect of waterlogging in wheat (T. aestivum L.). Acta Agriculturae Scandinavica Section B – Soil and Plant Science, 58(3), pp.193–198. https://doi.org/10.1080/09064710701508663
31. Pampana, S., Masoni, A. and Arduini, I., 2016. Grain yield of durum wheat as affected by waterlogging at tillering. Cereal Research Communications, 44, pp.706–716. https://doi.org/10.1556/0806.44.2016.027
32. Parihar, D.S., Narang, M.K., Dogra, B., Prakash, A. and Mahadik, A., 2023. Rice residue burning in northern India: An assessment of environmental concerns and potential solutions – a review. Environmental Research Communications, 5(6), p.062001. https://doi.org/10.1088/2515-7620/acd74f
33. Ploschuk, R.A., Miralles, D.J., Colmer, T.D., Ploschuk, E.L. and Striker, G.G., 2018. Waterlogging of winter crops at early and late stages: Impacts on leaf physiology, growth and yield. Frontiers in Plant Science, 9, p.1863. https://doi.org/10.3389/fpls.2018.01863
34. Prasad, R., Shivay, Y.S. and Kumar, D., 2017. Current status, challenges, and opportunities in rice production. In: T. Sasaki, ed. Rice Production Worldwide. Cham: Springer, pp.1–32. https://doi.org/10.1007/978-3-319-47516-5_1
35. Quemada, C., Pérez-Escudero, J.M., Gonzalo, R., Ederra, I., Santesteban, L.G., Torres, N. and Iriarte, J.C., 2021. Remote sensing for plant water content monitoring: A review. Remote Sensing, 13(11), p.2088. https://doi.org/10.3390/rs13112088
36. Rowland, A.P. and Haygarth, P.M., 1997. Determination of total dissolved phosphorus in soil solutions. Journal of Environmental Quality, 26, pp.410–415. https://doi.org/10.2134/jeq1997.00472425002600020011x
37. Seleiman, M.F., Al-Suhaibani, N., Ali, N., Akmal, M., Alotaibi, M., Refay, Y. and Battaglia, M.L., 2021. Drought stress impacts on plants and different approaches to alleviate its adverse effects. Plants, 10(2), p.259. https://doi.org/10.3390/plants10020259
38. Shao, G.C., Lan, J.J., Yu, S.E., Liu, N., Guo, R.Q. and She, D.L., 2013. Photosynthesis and growth of winter wheat in response to waterlogging at different growth stages. Photosynthetica, 51(3), pp.429–437. https://doi.org/10.1007/s11099-013-0044-6
39. Sharma, R., Kumar, R., Sharma, D.K., Son, L.H., Priyadarshini, I., Pham, B.T. and Rai, S., 2019. Inferring air pollution from air quality index by different geographical areas: Case study in India. Air Quality, Atmosphere and Health, 12, pp.1347–1357. https://doi.org/10.1007/s11869-019-00750-3

40. Ullah, A., Nawaz, A., Farooq, M. and Siddique, K.H., 2021. Agricultural innovation and sustainable development: A case study of rice–wheat cropping systems in South Asia. Sustainability, 13(4), p.1965. https://doi.org/10.3390/su13041965
41. Walkley, A. and Black, I.A., 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Science, 37(1), pp.29–38. https://doi.org/10.1097/00010694-193401000-00003
42. Wang, P. and Grimm, B., 2021. Connecting chlorophyll metabolism with accumulation of the photosynthetic apparatus. Trends in Plant Science, 26(5), pp.484–495. https://doi.org/10.1016/j.tplants.2020.12.005
43. Wu, X., Tang, Y., Li, C., Wu, C. and Huang, G., 2015. Chlorophyll fluorescence and yield responses of winter wheat to waterlogging at different growth stages. Plant Production Science, 18(3), pp.284–294. https://doi.org/10.1626/pps.18.284
44. Yadav, V.K., Kajla, M., Singh, S.P., Singh, A.K., Yadav, R.K. and Dwivedi, A.K., 2015. Effect of waterlogging tolerance in wheat (Triticum aestivum L.) at ear emergence stage on growth, biochemical and yield parameters in sodic soil. Journal of Applied and Natural Science, 7(2), pp.949–954. https://doi.org/10.31018/jans.v7i2.705
45. Zhao, H., Dai, T., Jing, Q., Jiang, D. and Cao, W., 2007. Leaf senescence and grain filling affected by post-anthesis high temperatures in two different wheat cultivars. Plant Growth Regulation, 51, pp.149–158. https://doi.org/10.1007/s10725-006-9152-x
46. Zhao, W., Liu, L., Shen, Q., Yang, J., Han, X., Tian, F. and Wu, J., 2020. Effects of water stress on photosynthesis, yield, and water use efficiency in winter wheat. Water, 12(8), p.2127. https://doi.org/10.3390/w12082127
47. Zheng, C., Jiang, D., Liu, F., Dai, T., Jing, Q. and Cao, W., 2009. Effects of salt and waterlogging stresses and their combination on leaf photosynthesis, chloroplast ATP synthesis, and antioxidant capacity in wheat. Plant Science, 176(4), pp.575–582. https://doi.org/10.1016/j.plantsci.2009.01.015