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Effect of Rice Crop Residue Burning on Soil Physico-Chemical attributes: A Study on Indian Soil

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BURNING of crop residue offers a cost-effective, easily accessible, and efficient method for handling in situ crop residues. This practice is prevalent in agriculturally intensive regions of India such as Punjab, Haryana, Rajasthan, and Uttar Pradesh. Burning residues releases harmful pollutants such as particulate matter, carbon monoxide, and volatile organic compounds into the atmosphere, contributing to air pollution. This pollution not only affects human health but also exacerbates climate change by increasing greenhouse gas emissions like CO_2 and methane. Additionally, burning residues leads to the loss of soil organic carbon and nutrients such as nitrogen, phosphorus, and potassium, which are essential for soil fertility and crop growth. With this in consideration, research aimed to assess the influence of rice crop residue burning in situ on soil physico-chemical attributes at CCSHAU, Hisar. Soil samples (0-15cm depth) were collected from the pre burning and burnt (0, 7, 14 and 21 days after burning) fields nearby villages of Tohana, Fatehabad (Haryana). Physico-chemical properties included soil bulk density, pH, electrical conductivity, organic matter, nitrogen, phosphorus and potassium content were investigated for pre and post burning soil samples. The data were analyzed statistically for ANOVA by using OPSTAT programme with CD values at 5% level of significance. Result analysis showed an increase in mean (0-21 days) pH, electrical conductivity and bulk density values of post-burning soil samples as compared to pre-burning (0 days) soil samples. A decrease in soil nitrogen, phosphorus and organic matter content was observed following stubble burning. But in contrast to these results, potassium content was found increased in post burning soil samples compared to pre burning.

Keywords: Agriculture, ANOVA, Climate change, Soil fertility, Stubble burning.

1. Introduction

The predominant agricultural system in South Asia revolves around the rice-wheat cropping pattern, wherein rice and wheat are cultivated in rotation throughout the year. Wheat ranks 1st in production and area of cultivation worldwide followed by corn, rice and barley as these are the major energy crop (Sharma et al., 2023; 2024a,b). The Asian region, including India, contributes significantly, accounting for about 90% of the world's rice production and consumption (Krishna and Meenakshi 2022). As an agrarian nation, India relies heavily on this system, which results in substantial quantities of crop residues. India generates an estimated 1043.24 million tonnes of gross crop residue annually. A significant portion is utilized for cattle feed, animal bedding, organic fertilizers, and as a fuel source for heating and cooking. However, around 356.7 million tonnes remain as surplus, which can be effectively used for power generation and other industrial applications (Chauhan et al., 2022).

Managing rice straw presents a significant challenge compared to wheat straw due to the limited time between rice harvesting and wheat sowing. Farmers in Punjab and Haryana face particular difficulties during November to December. Various options exist for managing crop residues, including burning, baling, incorporating into the soil in situ, removing residues, or retaining them partially or completely on the soil surface for mulching or as animal feed or bedding. However, farmers often opt for burning due to its ease and cost-effectiveness in quickly

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clearing fields (Dutta *et al*., 2022). Stubble burning during the winter months poses a significant concern due to the prominence of inversion conditions during this period. These conditions impede the dispersion of smoke emitted from burning, leading to reduced dilution in the atmosphere. Consequently, the smoke combines with fog, creating smog, which poses dangers to human health and the surrounding environment (Chawala and Sandhu, 2020). Crop residue burning is a significant issue not only in India but also in the Suqian region of Jiangsu Province, China. During 2001-2005, farmers in Suqian burned approximately 82% of wheat straw and 32% of rice straw in the fields due to mechanized harvesting. However, in Punjab and Haryana, unlike China, farmers tend to burn more rice residue than wheat residue (Lopes *et al*., 2023). The combustion of rice straw releases various gases, including carbon dioxide (70%), carbon monoxide (7%), methane (0.66%), and nitrous oxide (2.09%), adversely affecting air quality and human and animal health. Field burning in Punjab, Haryana, and Western Uttar Pradesh significantly contributes to these emissions (Jain *et al*., 2014). Various residue management practices including burning affect physico-chemical properties of soil significantly which includes bulk density, total NPK, soil organic matter (SOM), pH and EC. Stubble burning can affect soil properties through both direct and indirect means. Direct alterations occur during the fire itself, where heat or ash directly influences specific soil attributes. These immediate effects at the soil surface encompass fluctuations in nutrient concentrations, moisture levels, organic matter content, microbial populations, clay dispersion, aggregate cohesion, and soil hydraulic characteristics. Indirectly, outcomes like erosion, reduced organic content, and weakened aggregate cohesion typically arise as the soil surface undergoes erosion from wind and water over time. These changes are exacerbated by the reduction in organic matter levels resulting from stubble burning (Abdurrahman *et al*., 2020).

Crop residues burning significantly impacts both the physical and biological properties of soil. Moreover, it results in the depletion of crucial nutrients such as N, P, and K, along with the destruction of a substantial amount of valuable carbon. For instance, the combustion of rice stubble alone leads to the loss of approximately 0.445 million tonnes (Mt) of NPK annually. Similarly, wheat stubble burning causes a loss of around 0.144 Mt, while sugarcane waste burning results in a loss of about 0.84 Mt of NPK each year (Jain et al., 2014). Rice straw burning detrimentally affects soil health by causing degradation in soil properties and posing adverse impacts on plant and soil ecology (Parihar *et al.*, 2023). This agricultural practice significantly raises soil temperature, with observing an increase to 33.8°C–42.2°C at a depth of about 1 cm (Gupta e*t al*., 2004). Such heightened temperatures lead to the removal of N in various forms from the soil, ranging from 23% to 73%, causing rapid alterations in the soil's carbon-to-nitrogen (C:N) ratio within its uppermost layers (Kumar *et al*., 2015). Simultaneously, carbon is released into the atmosphere as CO_2, while N undergoes conversion into nitrate. These mechanisms result in the removal of approximately 824 thousand metric tonnes of N, P, and K constituents from the soil (Gupta *et al*., 2004). As a result, burning rice waste in the fields contributes to deteriorating soil health, which subsequently leads to reduced crop yields (El-Sobky, 2017; Abdurrahman *et al.*, 2020). Tripathi et al., (2015) observed minor changes in bulk density, pore space, specific gravity and water holding capacity, however significant changes (at 5% and 10% level of significance) were observed in temperature of the soil after burning of wheat residues. Edem *et al*., (2014) observed that burning soil with 30 and 90 kgm^{-2} of dry biomass increased bulk density by 4% and 9% respectively, while a 6% decrease in bulk density was noted with 120 kgm^{-2} of stubble materials.

Additionally, burning resulted in a significant reduction in total N content, whereas available phosphorus levels were higher in burnt plots compared to unburned soil. Kumar *et al*., (2019) found that post-burning, the soil pH significantly increased to 8.16 from 7.91 in the unburnt field. Additionally, the electrical conductivity (EC) of the soils rose markedly post-burning, reaching 0.09 dS/m compared to the pre-burning value of 0.078 dS/m. So, the stubble burning adversely affects the physico-chemical properties of soil. Converting agricultural residue to compost and biochar provides sustainable alternative for handling them (Khyalia et al., 2022; Malik et al., 2024). Also application of compost and biochar in agriculture field is reported to improve soil quality. Utilizing biochar combined with humic acids as organic soil conditioners can enhance soil properties and replenish nutrient deficiencies (Mousa, 2017; Ali 2018). Abouhussien et al. (2019) reported that the application of compost made from three different plant residues—maize, tomato, and vine—resulted in a reduction of soil pH, electrical conductivity (EC), and calcium carbonate ($CaCO_2$) levels. Integrated nutrient management is one of the approach which can also be followed if soil become deficient in nutrients (Singh et al., 2024).

Keeping in view the above concern, present study was conducted on impact of stubble burning on the physicochemical characteristics of soil.

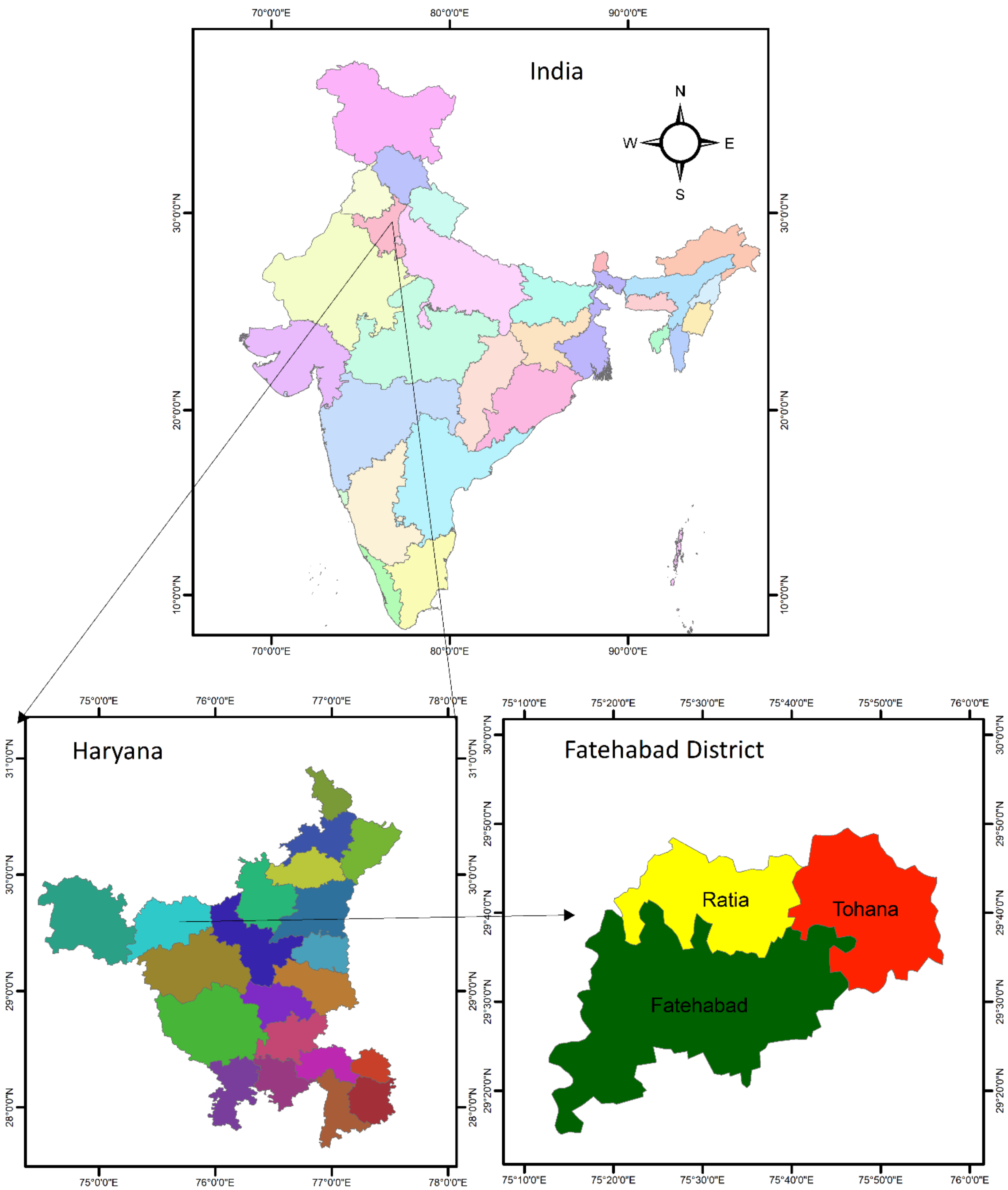

Fig. 1. Locations map of study area.

2. Materials and Methods

2.1. Soil sampling

Soil samples (0-15cm) were collected from the pre-burning and burnt (0, 7, 14 and 21 days after burning) fields nearby of Tohana, Distt. Fatehabad (Haryana) for soil parameters testing. Soil Samples were collected from 3 villages (3 sites from each village) named Khardwal, Samain and Bithmara (Fig. 1). The experiment was performed in Complete Randomized Design (CRD). Three replications were used for data analysis. Lab work was performed in the Department of Microbiology and Department of Botany and Plant Physiology, CCSHAU, Hisar.

2.2. Soil analysis

2.2.1. pH and Electrical Conductivity

The soil's pH and electrical conductivity were assessed using a handheld pH-EC meter (Microprocessor pH-EC Meter, 1611). To do so, 10 ml of distilled water was mixed with a 2 g soil sample, stirred for 5 minutes, and left to settle for a minimum of 30 minutes. Subsequently, the pH and EC measurements of the sample were taken.

2.2.2. Bulk density

The cylinder method (standard operating method) was used to calculate the bulk density of soil. Before oven drying, the initial mass of the cylinder with the sample was measured. Subsequently, one cap of the cylinder containing the sample was removed. The sample was positioned on the tray and moved to the oven, where it underwent drying at 105°C ±5°C for 24 hours or until reaching a consistent weight. Following this, the cap was reattached to the cylinder, and the sample was placed in the desiccator until it reached room temperature. Subsequently, the oven-dried mass of the sample was measured.

Bulk density = dry soil mass (g)/ volume of cylinder (cm^3)

2.2.3. Soil organic matter (SOM)

The Walkey-Black fast titration method was employed to estimate the amount of organic matter. A dried sample (1 g) was mixed with 10 mL K2Cr2O7 (1N) and 20 mL concentrated H2SO4, and the mixture was agitated for three hours. After one hour of standing, 200 mL of double-distilled water was added to the solution. A few drops of o-phenanthroline-ferrous complex indicator were added after that. A 0.5N ferrous ammonium sulphate solution was used to titrate the solution. The color of solution abruptly shifted from blue to a reddish-maroon tint in the conclusion. After taking note of the reading, the following formula was used to determine the percent (%) of organic carbon:

% Organic carbon = (control-sample) × 0.5 × 0.003 × 100 × correction factor/ Weight of soil

Correction factor: 1.33 for 1 g of sample

% Organic matter = % Organic carbon × 1.724

2.2.4. Total Nitrogen

Kjeldahl's method (Bremner and Mulvaney, 1982) was used to determine total nitrogen. The soil sample of 1.0 g was taken in each digestion tube along with 1.0 gram of digestion mixture containing K_2SO_4, $CuSO_4$, and SeO_2 in the ratio of 10:4:1 (w/w) and 15.0 ml of H_2SO_4. One tube was taken as control. After keeping overnight, it was digested on Kjeldahl digester for 1 hour at 420^0 C till bluish-green color appeared in the tube. Then these samples were distilled on a distillation unit with 50 ml of 40 % NaOH with 80 ml of distilled water, the sample turned black and the ammonia gas formed was trapped in 30 ml of 4% boric acid. Then the sample was titrated with 0.1 N HCl. The color changed from greenish blue to faint pink as the endpoint was reached.

The percentage of nitrogen was calculated by using the formula:

% N = 1.4 (S-B) × N/W

S = Vol. of acid used in the titration of sample (ml)

B = Vol. of acid used in the titration of blank (ml)

N = Normality of acid used for titration

W = Weight of the sample taken (g)

2.2.5.Total phosphorus

The method of Rowland and Haygarth (1997) was used to estimate total phosphorus. 500 mg of soil was taken in a 100 ml conical flask containing 10 ml of diacid mixture **{**nitric acid and perchloric acid in a ratio of 4:1 (v/v)}. The sample underwent digestion on a hot plate, followed by filtration and adjustment of the final volume to 100 ml. Total phosphorus content in the digested mixture was assessed after pH adjustment. Subsequently, aliquot of the digested solution was transferred into a 50 ml volumetric flask. Following the addition of 2 drops of 1.0% p-nitrophenol, 6.0 N NH4OH was introduced until a yellow color developed. The mixture was then titrated with 0.5 N HCl until it turned colorless. Subsequently, 5.0 ml of a combined reagent was included, and the volume was adjusted to 50 ml using distilled water. The UV-Vis spectrophotometer (Shimadzu UV-1800) measured the absorbance of the blue color at 882 nm after a 30-minute duration. The concentration of phosphorus in the solution was determined by comparing it to the values on the standard curve. For the creation of the standard curve, 2.5, 5.0, 10, 20, and 25 ml aliquots of the working standard (2.0 µg P/ml) were added to a 50 ml volumetric flask. Subsequently, distilled water was added to each flask to reach an approximate volume of 40 ml. 5.0 ml of a mixed reagent was added, and the volume was adjusted to achieve concentrations of 0.1, 0.2, 0.4, 0.8, and 1.0 µ g P/ml in the final solution, respectively. Subsequently, the absorbance of the blue color was measured at 882 nm using a UV-Vis spectrophotometer after a 30-minute interval.

Total P (%) = mg P/ml corresponding to absorbance × 100 × 100mg P/kg soil / ml of aliquot taken for color development × weight of soil (g)

2.2.6. Total Potassium

Total Potassium was estimated on a flame photometer by direct feeding. 1.0 g of soil sample was taken in a 150 ml conical flask and added 10 ml of diacid mixture. The sample underwent digestion on a hot plate, followed by filtration, and the volume was adjusted to 100 ml with distilled water. This digested solution was then utilized directly or, if needed, diluted based on the potassium concentration, for the determination of total potassium using a flame photometer. Potassium concentration was determined through a standard curve. This curve was established by noting the flame photometer readings for various working standard solutions with potassium concentrations of 5, 10, 15, 20, 25, and 40 µg ml^{-1}. The blank was set to zero, and 100 was calibrated at 40 µg ml-1 of potassium. Plotting these readings against the respective concentrations formed the standard curve.
Total K (%) = Concentration of K in ppm corresponding to flame photometer reading x dilution factor x 100 / weight of soil sample (g) x 10000

2.5. Statistical analyses

The data were analyzed statistically for ANOVA by using OPSTAT programme with CD values at 5% level of significance. Mean values were compared using Turkey's HSD test at $p < 0.05$. Values presented in tables are shown as the mean ± SE and labeled with different letters indicate a statistically significant difference from each other.

3. Results

Pre-burnt soil was brownish while post-burnt soil was blackish in color (whole soil). Soil texture analysis indicated that pre-burning soil samples contained 29% sand, 38% silt and 33% clay while post-burning soil samples contained 31% sand, 37% silt, and 32% clay (pooled data). Based on the soil texture analysis both pre-burnt and post-burnt soil can be characterized as clay loam. The experiment was conducted during Rabi season (2021-22). The results obtained for various parameters during the course of investigation are presented and discussed in this paper. Pre-burning results were compared with mean (0-21 days) results of post-burning conditions and percent change was calculated post-burning compared to pre-burning.

3.1. Impact on pH and EC

An increase in pH was observed in post-burning samples as compared to pre-burning samples as shown in Fig. 2. The maximum value of pH (7.76) was recorded at site 2 (Khardwal) and the minimum pH (7.26) was noted at site 9 (Bithmara) in pre-burning samples while in post-burning samples, the maximum mean value of pH (8.46) was recorded at site 3 (Khardwal) and the minimum mean value of pH (7.51) was recorded at site 1 (Khardwal). In post-burning samples, the maximum increase in pH (15.1%) was observed at site 7 (Bithmara) and minimum increase in pH (1.3%) was observed at site 6 (Samain) when mean values of post-burning period compared with the pre-burning samples. Within the post-burning period, slight but non-significant increase in pH values were observed in sites 1, 3 and 5 and a slight but non-significant decrease in pH values were observed at sites 6 and 9 from 0 to 21 days post-burning.
An increase in EC was observed in post-burning samples as compared to pre-burning samples as shown in Table 1. The maximum EC (1.09 dS/m) was recorded at site 2 (Khardwal) and the minimum value of EC (0.78 dS/m) was recorded at site 9 (Bithmara) in pre-burning samples while in post-burning samples, the maximum mean value of EC (2.13 dS/m) was recorded at site 4 (Samain) and the minimum mean value of EC (1.75 dS/m) was recorded at site 8 (Bithmara). And in post-burning samples, the maximum increase in EC (119.2%) was observed at site 7 (Bithmara) and minimum decrease in EC (86.4%) was observed at site 3 (Khardwal) when mean values of post-burning period compared with the pre-burning samples. Within the post-burning period, a slight but non-significant decrease in EC values were observed at sites 2, 4, 5, 6 and 7 from 0 to 21 days but non-significant increase was observed at other sites.

3.2. Impact on Bulk density

Bulk density of soil was found to increase in post-burning samples as compared to pre-burning samples. The highest bulk density (1.39 g/cc) of soil was recorded at site 5 (Samain) and the lowest bulk density (1.29 g/cc) of soil was recorded at site 7 (Bithmara) in pre-burning samples. while in post-burning samples, the highest mean bulk density (1.49 g/cc) of soil was recorded at site 5 (Samain) and the lowest mean bulk density (1.45 g/cc) of soil was recorded at site 1 (Khardwal). In the post-burning samples, the maximum increase in soil bulk density (14.2%) was recorded at site 7 (Bithmara) and minimum (5.3%) increase was recorded at site 1 (Khardwal) when mean values of post-burning period compared with the pre-burning samples. Within the post-burning period, a slight but non-significant decrease in bulk density was observed from 0-21 days in almost all the sites (Table 2).

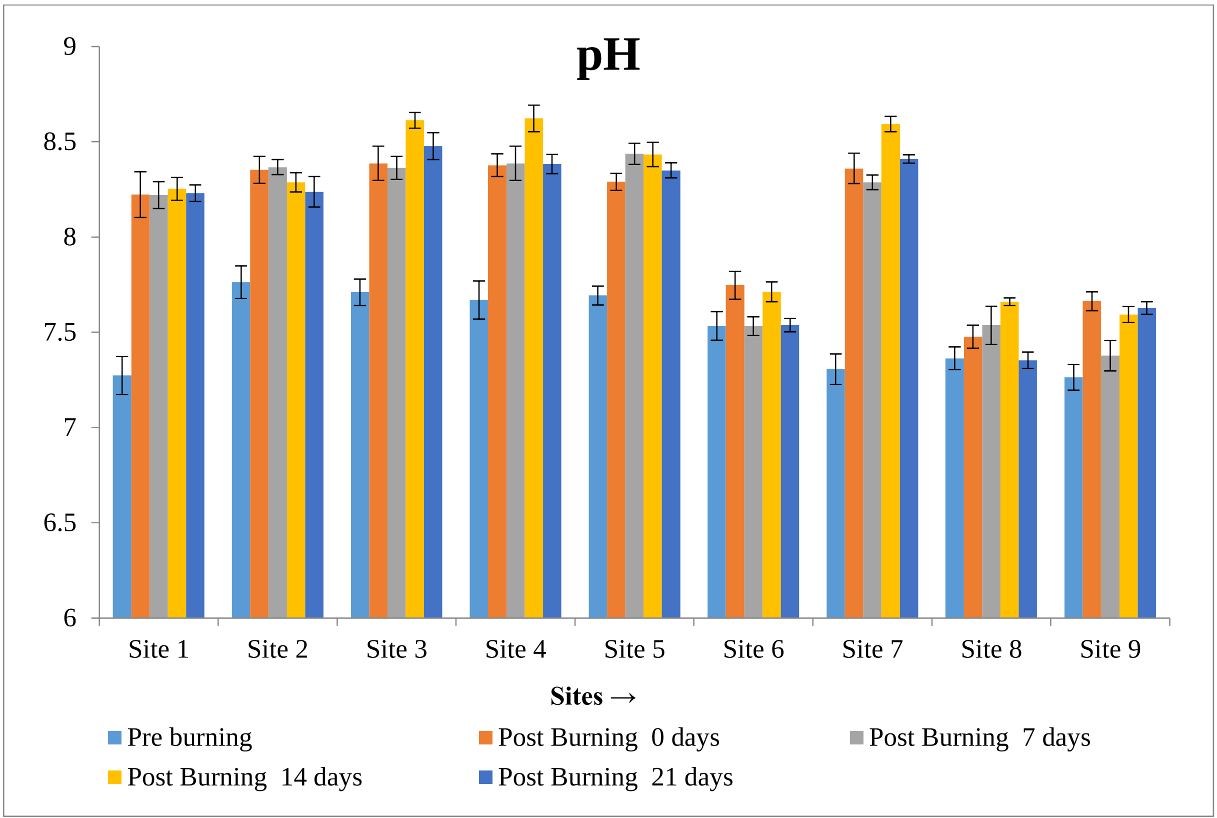

Fig. 2. Impact of *in situ* rice stubble burning on pH of soil (Data refers to mean ± S.E).

Table 1. Impact of *in situ* rice stubble burning on EC of soil (dS/m).

Village↓	Days→	Pre-burning	Post-burning 0 days	7 days	14 days	21 days
Khardwal	Site 1	0.85±0.01qrs	1.76±0.031klmn	1.77±0.038jklmn	1.73±0.006mn	1.81±0.019hijklmn
	Site 2	1.09±0.009o	2.13±0.036ab	2.08±0.044abcd	2.06±0.033bcde	2.01±0.039bcdef
	Site 3	0.99±0.005opq	1.84±0.023ghijklmn	1.86±0.039ghijklm	1.83±0.048hijklmn	1.85±0.032ghijklmn
Samain	Site 4	1.03±0.002op	2.21±0.026a	2.14±0.002ab	2.15±0.041ab	2.02±0.017bcdef
	Site 5	0.87±0.011qrs	1.88±0.004fghijkl	1.79±0.027ijklmn	1.81±0.031hijklmn	1.78±0.002jklmn
	Site 6	0.95±0.006opqr	1.91±0.016fghij	1.88±0.011fghijkl	1.89±0.047fghijk	1.85±0.018ghijklmn
Bithmara	Site 7	0.93±0.021pqr	2.11±0.005abc	2.01±0.012bcdef	2.06±0.013bcde	1.98±0.031cdefg
	Site 8	0.82±0.01rs	1.75±0.017klmn	1.81±0.035hijklmn	1.74±0.044lmn	1.71±0.023n
	Site 9	0.78±0.02s	1.93±0.018efghi	1.95±0.03defgh	1.91±0.044fghij	1.85±0.033ghijklmn

Table 2. Impact of *in situ* rice stubble burning on soil bulk density (g/cc) (0-15cm).

Village↓	Days→	Pre Burning	Post Burning 0 days	7 days	14 days	21 days
Khardwal	Site 1	1.380±0.016efghijk	1.480±0.017abcde	1.440±0.017bcdefgh	1.470±0.017abcdef	1.417±0.016cdefghij
	Site 2	1.370±0.009fghijk	1.490±0.017abcd	1.473±0.017abcdef	1.447±0.017abcdefg	1.470±0.017abcdef
	Site 3	1.340±0.012hijk	1.530±0.018ab	1.443±0.017bcdefgh	1.433±0.017bcdefghi	1.440±0.017bcdefgh
Samain	Site 4	1.330±0.008ijk	1.553±0.018a	1.433±0.017bcdefghi	1.480±0.017abcde	1.447±0.017abcdefg
	Site 5	1.392±0.01defghijk	1.520±0.018abc	1.470±0.017abcdef	1.500±0.017abc	1.470±0.017abcdef
	Site 6	1.350±0.012ghijk	1.480±0.018abcde	1.480±0.017abcde	1.427±0.017bcdefghi	1.460±0.017abcdef
Bithmara	Site 7	1.287±0.009k	1.510±0.017abc	1.450±0.017abcdefg	1.460±0.016abcdef	1.460±0.017abcdef
	Site 8	1.310±0.035k	1.520±0.017abc	1.440±0.017bcdefgh	1.480±0.017abcde	1.440±0.017bcdefgh
	Site 9	1.320±0.031jk	1.530±0.018ab	1.440±0.017bcdefgh	1.473±0.017abcdef	1.460±0.017abcdef

3.3. Impact on soil organic matter (SOM)

A reduction in soil organic matter (SOM) content was noted in post-burning samples compared to those collected before the burning event. Prior to burning, the highest SOM value (30,333.3 mg/kg) was documented at site 6 (Samain), while the lowest (28,233.0 mg/kg) was recorded at site 8 (Bithmara). Conversely, post-burning samples revealed that the maximum mean SOM value (28,419.8 mg/kg) was observed at site 1 (Khardwal), with the minimum mean values (26,147.9 mg/kg) found at site 8 (Bithmara). Regarding the decrease in SOM, post-burning samples exhibited the most significant decrease (8.1%) at site 9 (Bithmara), while the least decrease (5.5%) occurred at site 3 (Khardwal) when mean values of post-burning period compared to pre-burning samples. These findings suggest variations in SOM dynamics following burning events across different sites. Within the post-burning period, a slight increase in SOM was observed at site 1 and 3 from 0 to 21 days but no significant changes were observed at others sites (Table 3).

Table 3. Impact of *in situ* rice stubble burning on soil organic matter (mg/kg).

Village↓	Days→	Pre-burning	Post-burning 0 days	7 days	14 days	21 days
Khardwal	Site 1	30233.3±27a	28333±42def	28466.7±22de	28378.7±148def	28501±37de
	Site 2	29166.7±25bc	27117.7±22ij	27177.3±35i	27124.7±16ij	27326.3±58hi
	Site 3	29312±104bc	27467±26hi	27834.3±41fgh	27653±28ghi	27809.3±44fgh
Samain	Site 4	29167.3±41bc	27513±80hi	27423±90hi	27334±67hi	27369±52hi
	Site 5	29200±67bc	27447±40hi	27388±58hi	27433±64hi	27467.7±42hi
	Site 6	30333.3±89a	28132.7±39efg	28216.3±43defg	28168.7±84efg	28268±75def
Bithmara	Site 7	29412±100b	27332±111hi	27385.3±32hi	27262.3±61hi	27298.7±24hi
	Site 8	28233±103defg	26115±46k	26130±45k	26145.3±68k	26201.3±41k
	Site 9	28767±134cd	26532.7±36jk	26481±28k	26399.3±70k	26322±34k

3.4. Impact on Total NPK

A decline in the overall N concentration in soil samples following burning was noted in comparison to samples collected before the burning event. Prior to burning, the highest N content (663.4 mg/kg) was documented at site 3 (Khardwal), with the lowest (594.3 mg/kg) recorded at site 2 (Khardwal). Conversely, post-burning samples revealed that the maximum mean N value (551.6 mg/kg) was observed at site 3 (Khardwal), while the lowest mean values (504.0 mg/kg) were found at site 7 (Bithmara). In terms of the decrease in total N, post-burning samples exhibited the most significant decrease (20.8%) at site 7 (Bithmara) and the least decrease (14.2%) at site 1 (Khardwal) when mean values of post-burning period compared to pre-burning samples (Table 4). These findings suggest variations in soil nitrogen dynamics following burning events across different sites. During the post-burning period, slight but non-significant changes were observed in total N from 0 to 21 days across all sites.

The analysis from Table 5 indicates a reduction in soil total phosphorus content in samples collected after burning, in contrast to those collected before burning. In the pre-burning samples, the highest soil total phosphorus content (623.3 mg/kg) was observed at site 1 (Khardwal), while the lowest (581.7 mg/kg) was noted at site 8 (Bithmara). However, in the post-burning samples, the maximum mean total phosphorus value (561.6 mg/kg) was detected at site 3 (Khardwal), with the minimum mean value (480.4 mg/kg) at site 8 (Bithmara). Comparing the mean values of post-burning period to pre-burning samples, the greatest decrease in soil total phosphorus content (17.4%) was observed at site 8 (Bithmara), while the smallest decrease (9.3%) was found at site 3 (Khardwal). This suggests varying impacts of burning on soil phosphorus levels across different sites. During the post-burning period, slight but non-significant changes were observed in total P from 0 to 21 days across all sites.

The data from Table 6 indicates a rise in the overall potassium concentration in soil samples following burning, contrasting with those taken before the burning event. In the pre-burning samples, the highest potassium content (189.3 mg/kg) was documented at site 3 (Khardwal), while the lowest (160.7 mg/kg) was noted at site 8 (Bithmara). Conversely, in the post-burning samples, the maximum mean potassium value (223.7 mg/kg) was observed at site 2 (Khardwal), with the lowest mean values (199.9 mg/kg) at site 6 (Samain). Regarding the increase in total potassium, post-burning samples exhibited the most substantial increase (29.4%) at site 8 (Bithmara) and the smallest increase (14.5%) at site 3 (Khardwal) when mean values of post-burning period compared to the pre-burning samples. This suggests variations in soil potassium dynamics following burning events across different sites. Within the post-burning period, slight but non-significant changes were observed in total K from 0 to 21 days across all sites. Small fluctuations were observed in total K values a different time period within post-burning conditions as a slight increase in total K was observed at sites 2 and 3 from 0 to 7 days, followed by a decrease from 7 to 14 days post-burning.

Table 4. Impact of *in situ* rice stubble burning on total nitrogen of soil (total N, mg/kg).

Village↓	Days→	Pre-burning	Post-burning			
			0 days	**7 days**	**14 days**	**21 days**
Khardwal	**Site 1**	605.3±10.1cd	515±8.4ijklm	526.8±2.9efghijkl	521.5±1.1fghijklm	514.6±0.6ijklm
	Site 2	594.3±8d	509.3±4.8ijklm	509±2.3ijklm	512±4.4ijklm	507.1±3.7jklm
	Site 3	663.4±5.9a	550±2efg	552.5±3.4ef	555.4±8.7e	548.3±2.1efgh
Samain	**Site 4**	652.4±11ab	537.7±1.1efghij	525.5±2.2efghijklm	540.2±8.1efghi	533.2±2efghijk
	Site 5	613±8.6cd	519.5±3.2ghijklm	522.1±3.1fghijklm	518±4hijklm	531.3±1.9efghijk
	Site 6	605.7±8.5cd	509.4±2.4ijklm	504.5±1.2klm	527.3±2.2efghijkl	512±2.7ijklm
Bithmara	**Site 7**	636.5±11.9abc	495.3±1.9m	503±1klm	512.3±2.6ijklm	505.2±2.6klm
	Site 8	633±14.2abc	512.6±1.5ijklm	513±3ijklm	527±1.4efghijkl	514.3±3ijklm
	Site 9	623±7.1bcd	502.7±3.7klm	498.6±1.2lm	511.6±1.4ijklm	505.7±1.5klm

Table 5. Impact of *in situ* rice stubble burning on total phosphorus of soil (mg/kg).

Village↓	Days →	Pre-burning	Post-burning			
			0 days	7 days	14 days	21 days
Khardwal	Site 1	623.3±6.7a	555.3±3.8fgh	551±0.9fghi	549.7±2.3fghi	561.2±2.8ef
	Site 2	588.7±4.6bcd	512.3±1.6j	518.7±5.7jklmn	513.3±1.5jklmno	528.7±0.3ijk
	Site 3	619.3±4.9a	556±4.4fg	560±3.6ef	568±2.4def	562.5±3ef
Samain	Site 4	595.2±0.9bc	532.3±2ghij	528.5±4.5ijk	522±2.8jklm	531.8±3.2hij
	Site 5	591±8.9bcd	496.7±1.4nopqr	493.5±1opqr	502.6±2.5lmnopq	498.3±1.2mnopqr
	Site 6	582.3±6.7bcde	507±1.7klmnop	509.3±5.6jklmno	513.7±3.7jklmno	513.2±5.1jklmno
Bithmara	Site 7	606±0.9ab	502.7±1.6lmnopq	501.7±0.5lmnopq	507.3±2.8klmnop	505.4±4.2klmnop
	Site 8	581.7±0.9c	484±3.2pqr	479±1.3qr	477.4±1.7r	481±2.3qr
	Site 9	621.7±6.8a	518±3.4jklmn	525.3±4.4jkl	522.4±2.8jkl	519.7±3jklmn

Table 6. Impact of *in situ* rice stubble burning on total potassium of soil (mg/kg).

Village↓	Days →	Pre-burning	Post-burning			
			0 days	7 days	14 days	21 days
Khardwal	Site 1	167±5.5no	203.3±0.9defghijk	200±3.1ghijk	205.7±1.1cdefghijk	204.7±1.5cdefghijk
	Site 2	173.7±2.8mno	225±1.6ab	221.3±3.5abc	219.7±3.2abcd	228.7±0.4a
	Site 3	189.7±2.2klm	214.3±0.4abcdefgh	218.7±2.8abcde	219±3.7abcd	216.3±2.7abcdefg
Samain	Site 4	174.7±7mno	206±2cdefghijk	212.7±2.9abcdefghi	209±3.6bcdefghij	211.7±3.5bcdefghij
	Site 5	164.3±5no	204.3±0.1defghijk	198.7±0.2hijk	207.7±1.5cdefghij	201±1.5fghijk
	Site 6	165.8±2.4no	195±2.6jkl	202.3±3.8efghijk	196.7±1.9ijk	205.7±2.4cdefghijk
Bithmara	Site 7	178±1.7mn	211.3±1.7bcdefghij	207.7±1.2cdefghij	208.7±1bcdefghij	215.7±1.8abcdefg
	Site 8	160.7±4.4o	207.3±1.5cdefghij	203.3±0.6defghijk	209.7±4.1bcdefghij	211.3±1.8bcdefghij
	Site 9	178.3±3.4lmn	212.3±2.5abcdefghi	219±4.9abcde	214.7±4abcdefgh	217.7±2.3abcdef

4. Discussion

Burning crop residues is an inexpensive, convenient, and efficient method of managing on-site agricultural waste. Stubble burning affects soil properties directly or indirectly. An elevation in bulk density of up to 14.2% was noted in post-burning soil samples at a depth of 0-15cm (site 7, Bithmara) as shown in Table 2. This outcome aligns with the discovery that the heightened bulk density of soil stems from the depletion of organic matter and disruption of soil structure and composition due to heating. The rise in bulk density results from the collapse of soil aggregates and the filling of voids by ash and dispersed clay minerals, leading to decreased soil porosity and permeability (Boerner and Brinkman, 2003; Certini, 2005). Soil organic matter was found to decrease in post-burning samples up to 8.1% (site 9, Bithmara) as compared to the pre-burning soil samples as illustrated in Table 3. Stubble burning directly combusts crop residues, resulting in the loss of organic matter contained in the plant material. The heat produced during burning breaks down organic compounds, releasing carbon into the atmosphere instead of integrating it into the soil. Toan *et al*., (2022) similarly noted a 9% decrease in soil organic carbon (SOC) after burning compared to before.

In the present study, total nitrogen and phosphorus content were found to decrease in post-burning samples up to 20.8% (site 7, Bithmara) and 17.4% (site 8, Bithmara) respectively as compared to the pre-burning soil samples, but an increase in total potassium content were observed in post-burning samples up to 29.4% (site 8, Bithmara) as compared to the pre burnt soil samples as depicted in Table 4, 5 and 6. Our findings align with Kumar *et al*., (2019), indicating a notable reduction in soil N content post-burning, whereas available K showed an increase. The immediate effect can be attributed to the volatilization process during agricultural biomass burning, leading to decreased soil N and P levels. At 300°C, approximately half of the N in organic matter can undergo volatilization. The rise in total potassium content could result from the leaching of extractable potassium and cation mineralization from burnt crop residue. Kaur *et al*., (2019) found similar results that after burning, soil N and K levels decreased while potassium levels increased compared to before burning.

In the present study, an increase in pH and EC values were observed after residue burning up to 15.1% (site 7, Bithmara) and 25.2% (site 7, Bithmara) respectively as compared to pre-burning as shown in Fig 1 and Table 1. Our experiment results align with those of Kumar *et al*., (2019), indicating a notable rise in soil pH and EC post-burning in comparison to unburned fields. 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. Soil pH, a critical factor influencing soil fertility, is impacted by agricultural residue management practices. Burning residue elevates soil pH through ash deposition, primarily composed of alkali and alkaline earth metal carbonates, with varying amounts of sesquioxides, phosphates, silica, heavy metals, and minor inorganic and organic N content (Raison, 1979). Kaur *et al*., (2019) and Toan *et al*., (2022) observed similar results that the soil pH and EC increased significantly following burning.

5. Conclusion and Future Prospective

The experiment investigating the impact of in situ stubble burning on soil physico-chemical properties revealed several significant findings. Increased bulk density in post-burning conditions signs towards impaired physical structure of soil, while decreased levels of total nitrogen, phosphorus, and soil organic matter signs towards nutrient depletion in soil. Elevated pH and electrical conductivity (EC) values indicate towards increased salinity in soil post-burning. The data analyzed during the post-burning period indicates that the physico-chemical properties of the soil show no signs of recovery within the observed timeframe. The recovery of soil properties post-burning is complex and often takes longer than the initial period of analysis, depending on various factors such as fire severity, soil type, and environmental conditions. Overall, these results underscore the detrimental effects of stubble burning on soil health emphasizing the need for sustainable agricultural practices to mitigate these adverse consequences. Incorporating crop residues into the soil or composting them are more effective methods than stubble burning. These approaches enhance soil health and maintain its fertility, supporting sustainable agricultural practices. Long-term research highlights the importance of continuous monitoring and adaptation in crop residue management strategies.

Declarations

Ethics approval and consent to participate

Consent for publication: The article contains no such material that may be unlawful, defamatory, or which would, if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement.

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