**Original Research Article**

**Short-Term Impact of Rice Residue Burning and Management on Soil Nutrients and Crop Yield in a Rice-Wheat Cropping System**

**Abstract**

Stubble burning is a prevalent practice in the rice-wheat cropping systems of the Indo-Gangetic Plains, done primarily for rapid field clearance between paddy harvest and wheat sowing. This two-year field study conducted in Dakshin Dinajpur, West Bengal, evaluated the impact of short-term residue burning on some soil chemical properties - soil pH, available nitrogen, available phosphorus, available potassium and wheat yield, under both conventional tillage and zero tillage systems. Eight treatments were evaluated in a randomized block design at three soil depths. Results showed significant differences among the treatments across the soil profile. Residue burning caused a slight, temporary increase in topsoil pH but significantly reduced available nitrogen by 12-14% and phosphorus by 27-47% across all profiles, primarily due to nutrient volatilization and suppressed microbial activity, while potassium levels were only slightly affected. Wheat yields declined sharply under both conventional and zero tillage burning treatments compared to residue retention or incorporation. In contrast, conservation agriculture approaches maintained higher soil fertility and wheat yield. The highest grain yield of 5.64 t ha⁻¹ was recorded in T2, which corresponded to the conventional tillage with residue incorporated treatment. Hence, even under a short-term trial, these findings have shown the detrimental effects of residue burning, recommending conservation agriculture practices that retain or incorporate residues to sustain soil fertility and crop productivity.

**Keywords:** conservation agriculture, nutrient availability, rice-wheat cropping system, soil pH, stubble burning.

**1. Introduction**

The rice-wheat cropping system (RWCS) sustains food security and farmer livelihoods in India, covering nearly 9.2 million hectares, with about 85% of this area concentrated in the fertile alluvial soils of the Indo-Gangetic Plains (IGP) (Ladha *et al*., 2003; Jat *et al*., 2020). This system benefits from favourable climate, abundant water resources and high soil fertility. However, RWCS faces critical challenges related to crop residue management, particularly the management of rice straw after harvest. The mechanization of harvesting, especially through the wide adoption of combine harvesters, has significantly increased the volume of crop residues left in the field following rice harvest. These residues, typically stubble of around 25-30 cm height pose a challenge for quick and efficient field clearance necessary to meet the short time interval of about 10-15 days between rice harvesting and wheat sowing (Chawala and Sandhu, 2020). A typical stubble load of 4-5 Mg ha-1 obstructs seedbed preparation, compelling farmers to resort to rapid residue management methods that enable unhindered wheat cultivation within the narrow sowing window. As a result, open-field crop residue burning has become a widespread and convenient practice across the IGP.

It is estimated that about 92 million tonnes of crop residue are burned annually, with West Bengal contributing approximately 4.2 million tonnes and Punjab and Haryana together burning around 35 million tonnes from paddy fields each year (MNRE, 2009; Porichha *et al*., 2021). Despite its operational convenience and cost-effectiveness, residue burning is a major source of air pollution, contributing to 30-35% of particulate matter and causing PM2.5 concentrations to exceed 120 μg m-3 in affected areas (Singh and Kaskaoutis, 2014; Govardhan *et al*., 2023). This on-field burning not only affects atmospheric quality but also has detrimental long-term effects on soil health and crop productivity.

Residue burning triggers the volatilization of vital nutrients such as nitrogen, while phosphorus and potassium may partially remain but become less available due to ash convection, leaching and other processes (Gangwar *et al*., 2006; Are *et al*., 2009). The immediate effect may appear beneficial agronomically, with the removal of pests and disease pathogens from burned residues (Bescansa *et al*., 2006), but repeated burning leads to soil organic carbon depletion, pH alterations, reduced microbial biomass and disruption of enzyme activities essential for nutrient cycling (Tripathi *et al*., 2013; Kumar *et al*., 2019; Ahmad *et al*., 2024). Such degradation risks long-term soil fertility and productivity, undermining the sustainability of the rice-wheat system. In contrast, conservation agriculture (CA) practices have demonstrated potential in enhancing soil health and sustaining production. These include residue retention on soils and minimum or zero tillage (ZT), all of which improve soil organic matter content, moisture retention, microbial activity and nutrient cycling (Dalal *et al*., 2011; Gathala *et al*., 2015). For instance, ZT with residue retention over three years increased soil organic carbon compared to conventional tillage (CT) (Sinha *et al*., 2019), while incorporating crop residues has been shown to improve soil chemical properties and boost yields (Wang *et al*., 2015; Biswakarma *et al*., 2021). These changes are manifested as a result of the composition of rice straw which contains about 0.79% nitrogen, 1.97% phosphorus and 17.41% potassium on dry matter basis (Wang *et al*., 2020).

Despite these advantages, the adoption of CA in rice-dominated areas such as West Bengal remains limited. Economic constraints, lack of mechanized options for residue management, operational challenges and farmer preference for quick solutions like burning limit broader adoption of residue retention and zero tillage (Jain *et al*., 2014). Alternative uses of rice straw in West Bengal, such as livestock feed after alkali treatment, thatching materials, fuel and mushroom cultivation, reduce but do not eliminate residue volumes (Roy *et al*., 2015). With as low as 2% of farmers practicing zero tillage, there is a need for economically viable stubble management options suitable for local farmer conditions. With a general hypothesis that rules in favour of sustainable residue management practices, the objectives of this study were (i) to quantify the effect of short-term residue burning on chemical properties under different tillage systems on old alluvial soils in a rice-wheat cropping system (ii) to assess the effect of these practices on crop yield.

**2. Materials and Methods**

**2.1 Experimental Site and Climate**

The field experiment was conducted during two successive *rabi* seasons of 2021-22 and 2022-23 at the Instructional Farm, Regional Research Station (Old Alluvial Zone), Uttar Banga Krishi Viswavidyalaya, Majhian, Dakshin Dinajpur district, West Bengal, India (25°18' N, 88°45' E; elevation 15 m above mean sea level). The region, situated in the Lower Gangetic Plains, is characterized by old alluvial soils derived from Ganga sediments and features a humid subtropical climate. The average annual rainfall is 1690 mm, with about 66 rainy days. During the cropping seasons for the experiment, maximum average temperatures ranged from 21.7°C in January to 34.9°C in April, while minimum temperatures ranged from 9.5°C in January to 26.9°C in August. Relative humidity varied between 45% and 93%, highest during the monsoon, *i.e*., July to September and lowest during March to April.

**2.2. Soil Characteristics**

The experimental site soils are classified as clay loam soils with moderately to strongly acidic pH. Prior treatment imposition, samples were analysed to obtain baseline values. The results showed initial soil pH value at 5.46, available nitrogen 189.3 kg ha-1, available phosphorus 21.85 kg ha-1 and available potassium 286.3 kg ha-1 at the 0-10 cm depth.

**2.3 Experimental Design and Treatments**

A Randomized Block Design (RBD) was adopted, with eight treatments (T1 to T8) each replicated three times in 126 m2 plots (12 × 10.5 m). The experiment compared the effects of conventional tillage (CT) and zero tillage (ZT) systems combined with different residue management approaches, *viz*., residue removal, incorporation, burning and surface retention. The treatment combinations were, T1 - CT without residue (CT), T2 - CT + residue incorporation (CTR), T3 - CT + residue burning (CTRB), T4 - ZT + standing residues (ZTR), T5 - ZT + residue burning (ZTRB), T6 - ZT + standing residues + 3 t ha-1 extra loose straw (ZTR+3 t ha-1), T7 - CTR (Rice) / ZTR (Wheat) + 3 t ha-1 and T8 - Undisturbed control.

**2.4 Cropping Sequence and Cultural Practices**

Direct-seeded rice (*Oryza sativa* L., cv. Khitish) was grown in the *kharif* season, followed by wheat (*Triticum aestivum* L., cv. Karan Vandana) in the *rabi* season. Each year, rice was sown in July at 60 kg seed ha-1 (20 × 10 cm spacing) and wheat was sown in December at 125 kg seed ha-1 (22.5 × 10 cm spacing). CT plots underwent three passes with a tractor cultivator, two passes with a rotavator and subsequent planking while ZT plots were sown using a zero-till seed cum fertilizer drill without any prior soil preparation. For fertilization, rice received 60:30:30 kg N:P2O5:K2O ha-1 and wheat 100:50:50 kg ha-1, with N applied half as basal and half as top-dress in two equal splits. Pre-sowing and post-sowing irrigations were provided as per standard practice. Weed management included pre-emergence spraying with glyphosate and pendimethalin.

**2.5 Residue Management**

Immediately after rice harvest, anchored stubbles (20-25 cm) and surface straw were either incorporated, left as mulch or burned *in-situ*, according to the treatment. In T2 (CT + incorporation), straw and stubble were ploughed and mixed into the soil before wheat sowing. In burning treatments (T3, T5), stubbles were burned *in-situ*. In T6 and T7, additional measured quantities of loose straw (3 t ha-1) were spread as surface mulch along with retained stubble.

**2.6 Soil Sampling and Analysis**

At each main wheat growth stage (0, 15, 40, 80, and 120 days after burning), soil samples were drawn from each plot using an auger at 0-10, 10-20 and 20-40 cm depths. For each replicated plot, triplicate subsamples were collected and then about 500 g composite samples were prepared per treatment, depthwise. Soil pH was measured using a digital pH meter calibrated according to standard procedure. For this, a soil-to-water suspension was prepared in a 1:2.5 (w/v) ratio and the pH was recorded following the method described by Jackson (1973). Available nitrogen in the soil was determined through the alkaline potassium permanganate method, which estimates the amount of nitrogen released as ammonia after distilling soil with alkaline KMnO4, as outlined by Subbiah and Asija (1956). To assess available phosphorus, the Bray-I extraction method was employed, where soil was extracted with an acid fluoride solution and the phosphorus concentration in the filtrate was measured colorimetrically according to Bray and Kurtz (1945). Available potassium was determined by extracting the soil with neutral normal ammonium acetate, with the potassium content in the extract then quantified *via* flame photometry as per the method of Jackson (1973). Wheat grain and straw yields were recorded after air-drying the samples.

**2.7 Statistical Analysis**

All data were statistically analyzed using IBM SPSS Statistics 25. Main effects of treatments were tested using ANOVA (RCBD) with significance at *P* ≤ 0.05. Critical difference (CD) at 5% was calculated for pairwise comparison of significant differences. Means were separated using Duncan’s Multiple Range Test (DMRT).

**3. Results**

**3.1 Soil pH**

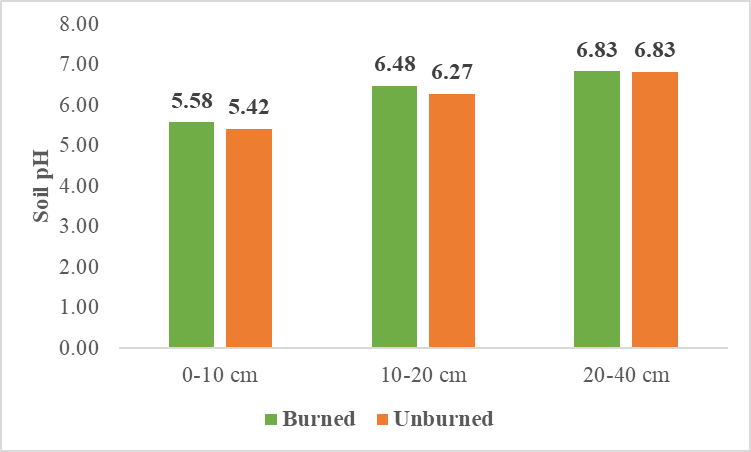
The mean values at the end of the second cropping cycle pooled over two years showed that residue burning led to a small but statistically significant increase in soil pH (Table 1), particularly in the topsoil layer. At the 0-10 cm depth, the residue burnt plots, T3 (CTRB) and T5 (ZTRB) exhibited average pH values of around 5.79, which was higher compared to 5.36 in the conventional tillage with residue incorporation treatment (T2) and 5.49 in zero tillage with residue retention (T6). This elevation arises from ash deposition containing base-forming cations such as calcium, potassium and magnesium ions which reduces soil acidity, primarily in the surface layer (Arunrat *et al*., 2023; Kumar *et al*., 2025). The effect was less pronounced but still evident at 10-20 cm depth, with no significant differences found beyond 20 cm, indicating that the influence of ash deposition was confined mainly to surface horizons. When an average was taken considering burned and unburned plots (Figure 1), at the 0-10 cm layer, soil pH in the burned plots was found to be higher (5.58) compared to the unburned plots (5.42). This trend persisted at the 10-20 cm depth but less prominently, where the pH in burned soils was 6.48 versus 6.27 in unburned soils. At the 20-40 cm layer, no difference was found, with both treatments recording an identical pH of 6.83.

**Table 1. Effect of rice residue burning and management on soil pH and wheat yield after**

**the second crop cycle pooled over two years in a rice-wheat cropping system**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Treatment** | **Soil pH (1:2.5)** | | | **Wheat yield (t ha-1)** | |
|  | **0-10 cm** | **10-20 cm** | **20-40 cm** | **Grain** | **Straw** |
| **T1** | 5.61ab | 6.49ab | 6.89abc | 4.50e | 6.22c |
| **T2** | 5.36bc | 6.23bc | 6.86bc | 5.64a | 7.29a |
| **T3** | 5.79a | 6.59a | 7.07a | 4.17f | 5.68d |
| **T4** | 5.42bc | 6.35ab | 6.96ab | 5.53a | 7.08a |
| **T5** | 5.36bc | 6.37ab | 6.59d | 4.69d | 5.79d |
| **T6** | 5.49b | 6.21bc | 6.74cd | 5.33b | 6.61b |
| **T7** | 5.39bc | 6.30bc | 6.74cd | 5.29b | 7.00a |
| **T8** | 5.16c | 6.07c | 6.60d | 5.10c | 6.22c |
| **S.Em.±** | 0.09 | 0.09 | 0.06 | 0.44 | 0.11 |
| **C.D. (*P* = 0.05)** | 0.90 | 0.89 | 0.76 | 2.01 | 1.01 |

Means with superscript values marked with different letters are significantly different (*P* ≤ 0.05) according to ANOVA. Values showing the same letter belong to the same homogeneous group according to Duncan’s test.



**Figure 1. Comparison of soil pH between burned and unburned plots at three depths**

**3.2 Available nitrogen**

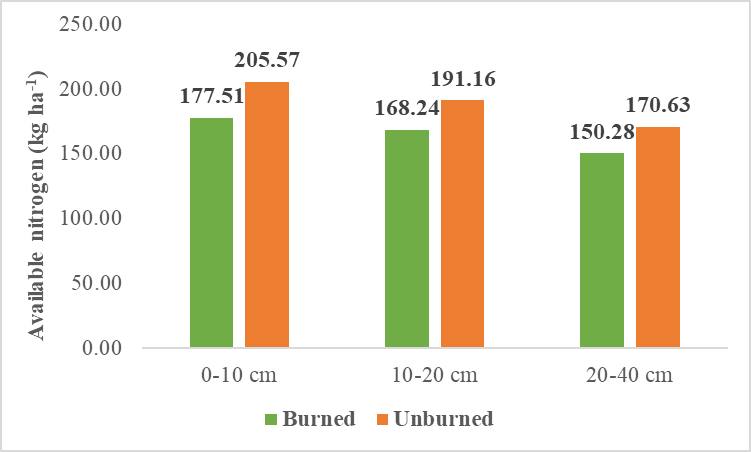
Burning significantly depleted available nitrogen (N) at all sampled depths, which was evident after the second cropping cycle, with the largest reductions occurring in the surface soil (Table 2). The highest available nitrogen values were consistently recorded in treatments with residue retention or incorporation across all depths, *i.e*., T6 (ZTR + 3 t ha⁻¹) which showed the highest value of 207.06 kg ha-1 at 0-10 cm and 190.98 kg ha-1 in the 10-20 cm layer, while T2 (CTR) had the highest N at 20-40 cm (173.44 kg ha-1). The lowest nitrogen values were observed in the burning treatments, T3 (CTRB) and T5 (ZTRB) which showed 13.68% lower values as compared to the averaged value of unburned treatments (Figure 2) and similarly low values were observed across all depths, with T3 recording 177.17 kg ha-1, 168.43 kg ha-1 and 150.39 kg ha-1, and T5 at 177.85 kg ha-1, 168.04 kg ha-1 and 150.16 kg ha-1 at 0-10 cm, 10-20 cm and 20-40 cm, respectively. This substantial loss of nitrogen results mainly from volatilization of organic nitrogen as ammonia gas and nitrogen oxides, which are rapidly lost to the atmosphere during burning and reduced microbial mineralization by loss of organic residues that otherwise replenishes plant available nitrogen (Lin *et al*., 2022; Gatkal *et al*., 2024). At deeper layers (10-20 cm and 20-40 cm), reductions in available nitrogen were observed, though less severely. At 10-20 cm, available nitrogen decreased by 11.98%, *i.e*., 168.24 kg ha-1 in burned plots and 191.16 kg ha-1 in unburned plots, while at 20-40 cm, the reduction was 11.91%, *i.e*.,150.28 kg ha-1 in burned treatments versus 170.63 kg ha-1 in unburned treatments, which showed that burning not only volatilizes surface nitrogen but also affects subsoil nitrogen dynamics as a result of reduced microbial activity and mineralization processes.

**Table 2. Effect of rice residue burning and management on available NPK after the**

**second crop cycle pooled over two years in a rice-wheat cropping system**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Treatment** | **Available nitrogen (kg ha-1)** | | | **Available phosphorus (kg ha-1)** | | | **Available potassium (kg ha-1)** | | |
| **Depth (cm)** | **0-10** | **10-20** | **20-40** | **0-10** | **10-20** | **20-40** | **0-10** | **10-20** | **20-40** |
| **T1** | 188.10b | 174.52b | 153.52c | 16.29c | 9.35bc | 3.24d | 282.52d | 240.33c | 192.28d |
| **T2** | 204.36a | 192.09a | 173.44a | 25.78a | 16.11a | 4.91b | 294.06ab | 254.73a | 198.06ab |
| **T3** | 177.17c | 168.43c | 150.39c | 19.37b | 10.60b | 3.07d | 284.82cd | 247.07b | 194.86cd |
| **T4** | 205.76a | 191.80a | 170.33ab | 27.08a | 16.92a | 6.14a | 294.57a | 255.75a | 198.81a |
| **T5** | 177.85c | 168.04c | 150.16c | 18.78b | 10.15bc | 3.15d | 288.90bc | 248.01b | 195.52bc |
| **T6** | 207.06a | 190.98a | 171.27ab | 26.33a | 15.92a | 6.15a | 295.11a | 255.10a | 198.99a |
| **T7** | 205.08a | 189.78a | 167.46b | 25.71a | 15.81a | 6.10a | 294.18ab | 256.17a | 197.93ab |
| **T8** | 182.85bc | 172.82bc | 152.52c | 16.83c | 9.20c | 3.79c | 272.12e | 234.66d | 187.27e |
| **S.Em.±** | 2.39 | 1.98 | 1.57 | 0.67 | 0.44 | 0.10 | 1.80 | 1.66 | 1.00 |
| **C.D.(*P =* 0.05)** | 4.68 | 4.26 | 3.80 | 2.48 | 2.00 | 0.96 | 4.08 | 3.91 | 3.03 |

Means with superscript values marked with different letters are significantly different (*P* ≤ 0.05) according to ANOVA. Values showing the same letter belong to the same homogeneous group according to Duncan’s test.

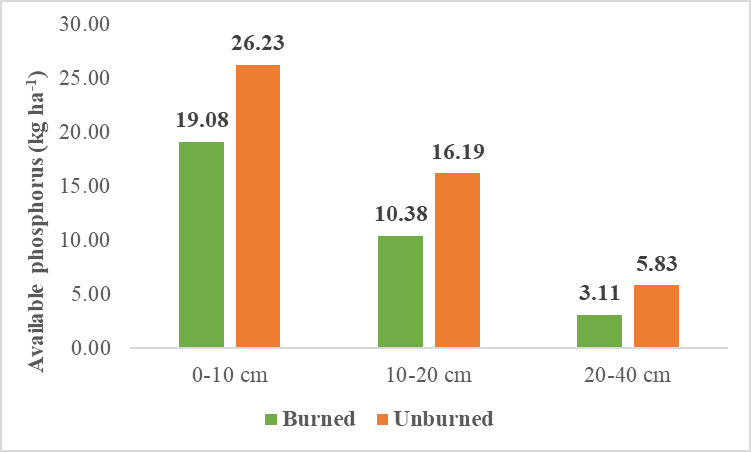


**Figure 2. Comparison of available nitrogen between burned and unburned plots at**

**three depths**

**3.3 Available phosphorus**

Available phosphorus (P) showed marked declines with residue burning. At the 0-10 cm surface layer, available phosphorus in unburned plots was 26.23 kg ha-1, whereas burned plots recorded a reduced value of 19.08 kg ha-1 (Figure 3). This amounts to a 27.25% decrease in plant available phosphorus under burned conditions compared to unburned conditions. In the 10-20 cm depth, available phosphorus declined from 16.19 kg ha-1 in the unburned plots to 10.38 kg ha-1 in burned plots, corresponding to a 35.89% reduction. The negative impact was most severe at the 20-40 cm depth because burning reduced available phosphorus from 5.83 kg ha-1 to 3.11 kg ha-1, a decline of 46.65%. At the 0-10 cm depth, available phosphorus was highest under zero tillage with standing residues (T4), recording 27.08 kg ha-1, followed closely by zero tillage with standing residues plus 3 t ha-1 loose straw (T6) at 26.33 kg ha-1 and conventional tillage with residue incorporation (T2) at 25.78 kg ha-1 (Table 2). The lowest value among the burning treatments was observed in conventional tillage with burning (T3) with a value of 19.37 kg ha-1. In the 10-20 cm layer, available phosphorus was highest in T4 with 16.92 kg P ha-1. T6 with 15.92 kg P ha-1 and T2 with 16.11 kg P ha-1 followed close behind whereas T1 (CT without residue) recorded the lowest value of 9.35 kg P ha-1. At 20-40 cm, T6 had the highest phosphorus (6.15 kg ha-1), marginally above T4 (6.14 kg ha-1) and T7 (6.10 kg ha-1), whereas T1 showed the lowest value (3.24 kg ha-1). These results demonstrated that treatments involving residue retention or incorporation, especially under zero tillage, preserved higher soil phosphorus at all depths, while removal or burning led to the lowest values, a trend attributed to enhanced microbial activity due to the rice residues which lead to better organic matter cycling under CA oriented practices as confirmed by the findings of Sharma *et al*. (2022), Dutta *et al*. (2024) and Gupta *et al*. (2024).

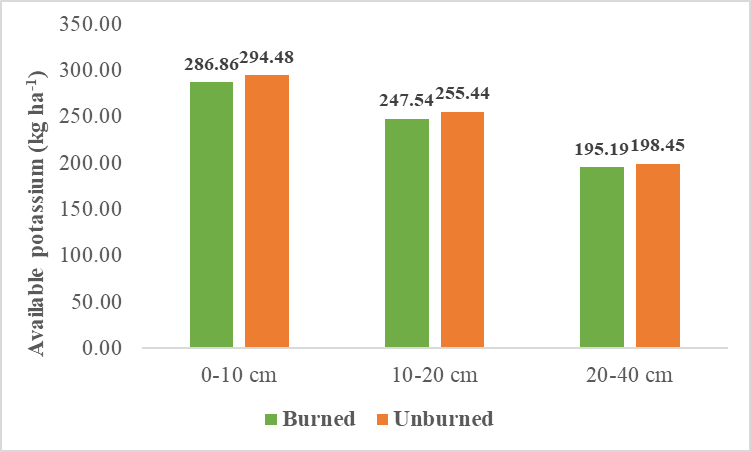


**Figure 3. Comparison of available phosphorus between burned and unburned plots at**

**three depths**

**3.4 Available potassium**

Available potassium (K) levels were relatively stable compared to N and P, showing only a slight reduction in burned treatments (Table 2). It had low variations across treatments with the highest values observed in zero tillage with residue retention or added straw, *i.e*., T4 at 294.57 kg ha-1 and T6 at 295.11 kg ha-1 at 0-10 cm depth, as well as in the alternate tillage treatment, T7 at 294.18 kg ha-1 and conventional tillage with residue incorporation, T2 at 294.06 kg ha-1. Burning treatments showed intermediate potassium availability with conventional tillage with burning (T3) recording 284.82 kg ha-1 and zero tillage with burning (T5) recording 288.90 kg ha-1, both consistently lower than residue-retaining treatments but only slightly higher than residue removal treatment T1 which recorded a value of 282.52 kg ha-1. Similar patterns were observed at deeper layers, with burned plots (T3 and T5) maintaining lower K values compared to residue retention but higher than complete removal. Overall, residue burning resulted in only minor reductions of about 2-4% in surface and subsurface potassium relative to residue incorporation or retention, owing to potassium being non-volatile during burning and its considerable presence in the ash derived from rice residue burning (Figure 4). However, residue management under zero tillage best sustained K availability across the soil profile (Fu *et al*., 2021; Sadiq e*t al*., 2024).



**Figure 4. Comparison of available potassium between burned and unburned plots at**

**three depths**

**3.5 Crop yield**

Wheat grain yields were significantly influenced by residue and tillage management practices, with residue burning reducing yield due to the combined depletion of soil nutrients, nitrogen and phosphorus, organic carbon and microbial activity (Table 1). The lowest grain yields were consistently recorded in residue burning treatments, with conventional tillage with residue burning (T3) producing an average of 4.17 tonnes per hectare (t ha-1), representing a 26% reduction compared to 5.64 t ha-1 in conventional tillage with residue incorporation (T2). Zero tillage with standing residues (T4) and zero tillage with standing residues plus loose straw (T6) also achieved comparable high grain yields of 5.53 t ha-1 and 5.33 t ha-1, respectively, indicating that residue retention under zero tillage can sustain productivity levels similar to residue incorporation. Under zero tillage with residue burning (T5), grain yield moderately declined to 4.69 t ha-1, significantly lower than residue-retaining treatments but marginally higher than T3, *i.e.* CTRB. T7, which corresponded to alternate management involving conventional tillage with residue incorporation in rice followed by zero tillage with residue retention and added straw in wheat, produced a yield of 5.29 t ha-1, significantly outperforming residue burning and residue removal treatments. Straw yield patterns mirrored grain yield trends, with the highest straw produced in conventional tillage with residue incorporation (7.29 t ha-1), zero tillage plus standing residues and loose straw (6.61 t ha-1) and the alternate tillage treatment (7.00 t ha-1). The lowest straw yields occurred in residue burnt plots, with CTRB at 5.68 t ha-1 and ZTRB at 5.79 t ha-1. These results have shown that residue burning under both conventional and zero tillage systems significantly diminishes wheat grain and straw yields compared to residue incorporation or retention. CA practices that maintain or add surface residues, particularly within zero tillage systems, effectively conserve soil fertility and moisture, support microbial activity and thereby enhance wheat productivity (Goswami *et al*., 2019; Sidhu *et al*., 2024).

**4. Discussion**

Residue burning led to a small and temporary increase in surface soil pH, owing to alkaline ash deposition and caused depletion in available nitrogen and phosphorus and ultimately in wheat yield (Mirzaei *et al*., 2021; Kumar *et al*., 2023). The reduction in available nitrogen by approximately 12-14% following burning, primarily results from volatilization of organic and ammoniacal N at high temperatures, enhanced by suppression of microbial activity and subsequent limitations on nitrogen mineralization and cycling (Holman *et al*., 2023). Available phosphorus exhibited the most serious decline, with up to 27-47% loss across the soil profile in burned treatments. Organic matter and active microbial communities are critical for supporting the mineralization processes and particularly the enzymatic release of phosphorus from organic pools which provide much of the available phosphorus in alluvial soils (Mabagala, 2022). Burning sharply reduces these biological processes not only at the surface but also affects subsoil layers by decreasing root biomass and the downward flux of labile carbon (Ono *et al*., 2025). This results in a limited supply of fresh organic materials and suppressed phosphatase enzyme activity in the lower layers, thus causing a substantial reduction in available phosphorus there (Reddy *et al*., 2022). Conversely, potassium levels reduced only slightly by about 1.6-3% due to its presence in ash. These patterns indicate that even a single burning event imparts persistent changes on the fertility of soil (Dhanda *et al.,* 2022). In direct alignment with the changes in the macronutrients content, wheat yields declined significantly in burning treatments compared to residue incorporation or zero-tillage with surface retention. While previous studies have documented residue burning effects in the Indo-Gangetic belt, most were conducted on neutral to slightly alkaline soils or over multi-year burning scenarios. Yield reductions seen in several long-term studies in subtropical rice-wheat systems is found to be consistent with this short-term study showing the sensitivity of acidic alluvial soils with low organic matter content in India to burning-induced degradation. On the other hand, the fact that CA approaches lead to gradual improvement of organic carbon and soil quality, while mitigating acidification was reinforced (Rodriguez *et al*., 2022; Teng *et al*., 2024). Despite some initial implementation hurdles, such as nitrogen immobilization or weed pressure, the evidence here argues for the net agronomic and ecological advantage of conservation strategies over burning even in short-term trials.

**5. Conclusion**

Short-term *in-situ* burning of rice residues results in a slight surface pH increase but causes severe losses in available nitrogen and phosphorus with declines in wheat yield. Potassium availability remains largely stable, although with minor losses due to ash removal. Conservation agriculture through residue incorporation or zero tillage with surface retention effectively preserves soil fertility and enhances wheat yield, offering a sustainable alternative to residue burning. There is a need for farmer education initiatives to promote conservation-oriented residue management in Indo-Gangetic alluvial rice-wheat systems.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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