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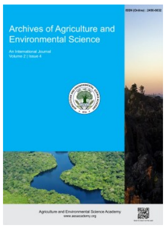

ORIGINAL RESEARCH ARTICLE

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Variation in soil properties due to on-field residue burning in sugarcane based agro-ecosystems of Central India

Richa Kumari[1,2], Pranab Kumar Pati[1*], Priya Kaushik[1], Mohammed Latif Khan[1] and Pramod Kumar Khare[1]

[1]Ecology laboratory, Department of Botany, Dr. Harisingh Gour Vishwavidyalaya (A Central University), Sagar, M.P., 470003, India
[2]Department of Botany, Maharana Pratap Govt. P.G. College, Gadarwara, Narsinghpur, M.P., 487551, India
[*]Corresponding author's E-mail: pranabpati9040@gmail.com

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ABSTRACT

Crop residue burning is a widespread practice in India that significantly affects the environment, climate, human health, and soil quality by altering nutrient dynamics and soil biological activity. Despite its known adverse consequences, it remains a common residue management method. The present study was conducted during 2022-2023 across three sugarcane fields in Narsinghpur district of Madhya Pradesh, to evaluate the short-term effects of sugarcane residue burning on soil physicochemical properties. Soil samples were collected before and after burning within the same cropping season to assess immediate changes. Results revealed increases in soil pH (8.05 to 8.13), electrical conductivity (110.69±14.27 to 163.09±4.78 µs/ppm), soil organic carbon (1.02±0.19 to 1.15±0.16 %), phosphorus (21.26±7.73 to 22.95±7.80 kg/ha), manganese, iron, and zinc. In contrast, nitrogen (56.45±3.62 to 54.35±5.53 kg/ha), potassium (162.97±14.17 to 133.77±11.50 kg/ha), and copper (1.92±0.09 to 1.73±0.05 µg/g) declined. Compared to pre-burn conditions, on-field residue burning increased soil organic carbon and phosphorus by 12.75% and 7.95%, respectively, while reducing potassium and nitrogen by 21.83% and 3.84%. Overall, the investigation indicates that residue burning leads to a short-term improvement in certain soil chemical properties, likely due to ash deposition, but also results in nutrient imbalances and losses of essential elements such as N, K, and Cu. These findings highlight the transient nature of nutrient enrichment following burning and emphasize the need for long-term studies to assess its sustained effects on soil health.

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INTRODUCTION

Fire incidents are currently one of the major sources of greenhouse gas emissions worldwide that significantly contribute to the global event of climate change (Bowman *et al*., 2020; Singh, 2022; Pati *et al*., 2024; Pati *et al*. 2025a). Alike fires in forests and savannas, crop residue burning is one of the major forms of biomass burning which alone constitutes approximately 8-11% of global biomass burning (Korontzi *et al*., 2006). Furthermore, it is one of the major sources of atmospheric pollution and possesses adverse effects on human health (Reddy & Chhabra, 2022). Despite the understanding of its disastrous effects, it is still a well-approached method in many regions of the world (Souza *et al*., 2012; Kaur *et al*., 2019; Fu *et al*., 2021; Dutta *et al*., 2022; Kumari *et al*., 2023), which may be due to its perceived benefits such as weed management, pest prevention, disease control (Lohan *et al*., 2018; Kaur *et al*., 2021) and the provision of ash as fertilizer (Korontzi *et al*., 2006; Dutta *et al*., 2022). Therefore, it urges a serious attention, particularly in light of the current food scarcity and the growing global population.

India, one of the world's largest economies, depends largely on agriculture for its revenue to drive economic growth (Mathur &

Srivastava, 2019). In addition, it is the most populous country in the world which primarily depends on the agricultural goods and commodities including wheat, rice, pulses and sugarcane to feed and sustain its enormous and increasing population (Dutta *et al.*, 2022). In order to meet the demands of an expanding population, food production has recently been under tremendous pressure both globally as well as in India, which offers farmers a limited timeline of opportunity (usually three to four weeks) to make adjustments before the next farming session (Kaur *et al.*, 2019; Reddy & Chhabra, 2022). As a result of expanding agricultural productivity, crop residues consequently result in a larger mass of waste which, if unmanaged, significantly contributes to environmental pollution (Dumka *et al.*, 2019). Crop waste has historically been utilized as animal feed, commercial fuel and for domestic cooking (Kumari *et al.*, 2023). However, due to the unavailability of economical and efficient technologies, farmers generally practice residue burning as a solution to get rid of agricultural waste and prepare the field for the next cropping season as it is inexpensive, easy to execute and less time-consuming (Singh & Sidhu, 2014; Reddy & Chhabra, 2022; Dutta *et al.*, 2022).

As a result of increasing agricultural activities, crop residue generation in India is continuously increasing; for example, during the year 1994, 217 Tg of crop residues were generated, which further increased to 253 Tg in 2010, along with a burn percentage of 20.74% and 24.90% respectively. As a result, it produced around 174.0 Gg of CH_4, 3.9 Gg of N_2O, 3431.4 Gg of CO and 140.6 Gg of NO_x during the year 2010 which is approximately 16% higher than the year 1994 (Sahai *et al.*, 2011). Previous studies in India related to the assessment of the impacts of crop residue burning are mostly confined to the states of Punjab, Haryana, Rajasthan and Uttar Pradesh (Singh *et al.*, 2020; Mor *et al.*, 2023; Desouza *et al.*, 2023; Dhaliwal *et al.*, 2022; Downing *et al.*, 2022; Sharma *et al.*, 2024; Singh *et al.*, 2024; Neelam *et al.*, 2024; Saharan *et al.*, 2024). However, an earlier study by Verma *et al.* (2019) documented the increasing agricultural residue burning activities in different parts of the state of Madhya Pradesh for the year 2016, which is almost ten times more than that in 2002 with an annual increase rate of 64%. Further, Deshpande *et al.* (2023) identified Madhya Pradesh as the second largest contributor to crop residue burning, accounting for approximately 30% of the nation's total burned area with a steadily rising number.

Rice, wheat, soybeans, sugarcane, and maize are the principal crops cultivated in different parts of the state of Madhya Pradesh along with lesser areas of cotton, mustard, peanuts, urad, jowar, moong, gram, and tur (Kumari *et al.*, 2023). According to the agriculture department of Madhya Pradesh, the state produces approximately 33 million tons of crop residues annually, of which 80% is contributed by cereal crops especially wheat and paddy, with an on field burning quantity of 3.6 million tones which releases around 5.676 Mg/year of greenhouse gases, of which carbon dioxide, methane and nitrous oxide contribute around 5.666 Mg/year, 10.10 kg/year and 0.26 kg/year respectively (Satyendra, 2015). As an emerging state for crop residue burning, research in the state of Madhya Pradesh is a prerequisite to comprehend the effects of various climatic and geographical conditions as well as different cropping systems.

In addition to environmental and human health impacts due to greenhouse gas emissions, crop residue burning can also deplete the biological, physiochemical and biochemical properties of soil (Abdurrahman *et al.*, 2020; Fu *et al.*, 2021; Dutta *et al.*, 2022; Kumari *et al.*, 2023; Arunrat *et al.*, 2023). For instance, it can deteriorate soil quality by releasing essential nutrients that are important for growth and survival including potassium, phosphorus, nitrogen, and organic carbon (Porichha *et al.*, 2021). Further, the soil's temperature can rise to 35.8–42.2°C due to crop residue burning (Jitendra *et al.*, 2017), which could lead to a decline in beneficial microorganisms that affect soil productivity, such as mycorrhiza and bacteria that fix nitrogen (Kumar *et al.*, 2019a; Bhuvaneshwari *et al.*, 2019; Reddy & Chhabra, 2022). In addition, burning of crop residues not only reduces native soil nutrients, but also destroys the available nutrients in the stubble and crop residues (Fu *et al.*, 2021; Dutta *et al.*, 2022; Sharma & Singh, 2023; Liu *et al.*, 2023; Brichi *et al.*, 2023; Pingthaisong *et al.*, 2024). As a result, the quality of the soil gets depleted which is detrimental to sustainable agriculture.

Literature review on crop residue burning for the Indian continent revealed that despite growing interest in aspects related to the biological functioning of soil under agricultural systems, studies on the impacts of crop residue burning are still lacking to provide conclusive evidence to draw firm conclusions in an agriculturally important country like India. Although, several studies have been conducted to evaluate the effects of burning crop residues, their scope was primarily limited to evaluating the effects on greenhouse gas emissions and subsequent environmental contamination (Dhaliwal *et al.*, 2022; Deshpande *et al.*, 2023; Sharma *et al.*, 2024; Singh *et al.*, 2024; Saharan *et al.*, 2024). In addition, although few studies have attempted to evaluate the effects of burning crop residue on soil properties, they were primarily confined to rice and wheat agricultural fields, neglecting other significant crops such as sugarcane (Mandal *et al.*, 2004; Kaur *et al.*, 2019; Kumari *et al.*, 2023).

In India, sugarcane generates approximately 26.2 Tg of crop residues annually, comprising dry leaves and sheaths, tops, and bagasse. Among these, dry leaves and sheaths and tops are the major contributors of field residues and are often subjected to open-field burning, while bagasse is almost entirely utilized as fuel in sugar industries (Sahai *et al.*, 2011), making the management of field residues critical for both environmental sustainability and soil health. In addition, the chemical composition of sugarcane differs from that of other crops, including rice and wheat (de Moraes Rocha *et al.*, 2015; Dutta *et al.*, 2022). The effects of sugarcane residue burning on soil sub-systems are likely to vary compared to those of rice and wheat as (i) it requires a significantly higher proportion of water for cultivation, (ii) it has a difference in the quantity of minerals in its residues and (iii) it generates a comparatively higher amount of residues which may increase the burn severity. Further, the soil and environmental conditions associated with sugarcane cultivation are different from those of rice and wheat agricultural systems, which could result in variance in the effects. The present investigation aimed to assess the effects of sugarcane residue burning on soil properties and nutrient dynamics in agricultural fields of the Narsinghpur district of Madhya Pradesh, Central India.

MATERIALS AND METHODS

Study area

The study was carried out at three distinct sugarcane fields in the Narsinghpur district, Madhya Pradesh, India. It is situated in the central part of the state, between 22.95°N latitude and 79.2°E longitude with an elevation of 347m above mean sea level. Its northern region is surrounded by the Vindhyan range, whereas the Satpura range in Central India completely encloses the southern region. The maximum and minimum temperatures recorded in the study area were 44°C and 25°C, respectively, with a mean annual rainfall of 1016 mm. The Narmada River flows from east to west in the northern part of this district. Fertile black soil is found in most of the parts of this district. This area is mostly used for the cultivation of kharif crops, such as sugarcane, paddy, jowar, bajra, corn (makka), kondo and kutki and rabi crops such as wheat, pulses, peas, flax (alsi), and lentils (masoor).

Standard agronomic practices were followed across all study sites, including conventional tillage, scheduled irrigation, recommended fertilizer application, and manual harvesting. For the experimental purpose, three sugarcane (*Saccharum officinarum* L.) cultivation sites were selected (Figure 1). In this region, sugarcane stalks are manually cut and transported to nearby sugar mills, leaving behind a substantial quantity of crop residues in the field. These residues, collectively termed sugarcane residues, primarily consist of dry leaves, leaf sheaths, and the upper portions (tops) of the sugarcane stalks that are not suitable for processing. The accumulated residue forms a dense layer on the soil surface, which farmers typically burn in situ to facilitate field clearing and prepare the land for the subsequent planting cycle. The burning process usually takes place during the harvest season (October–April) under dry weather conditions, when the residue has low moisture content and is highly combustible which formed the basis for assessing the changes in soil properties before and after burning. Study site selection was based on the history of burning practices, types of crops cultivated, growing season of crop, amount of residue generated and frequency and periodicity of burning. The study was conducted over a one-year cropping cycle (2022-2023), encompassing both pre-burning and post-burning sampling stages to capture variations in soil responses. The sugarcane fields selected for the study were managed under standard farmer practices, including the application of manures and fertilizers according to local norms. No experimental manipulation of agronomic practices was undertaken to avoid altering natural conditions or disrupting farmer operations. Residue burning was carried out in accordance with farmers' routine post-harvest practices, ensuring that the observations reflected real-field conditions.

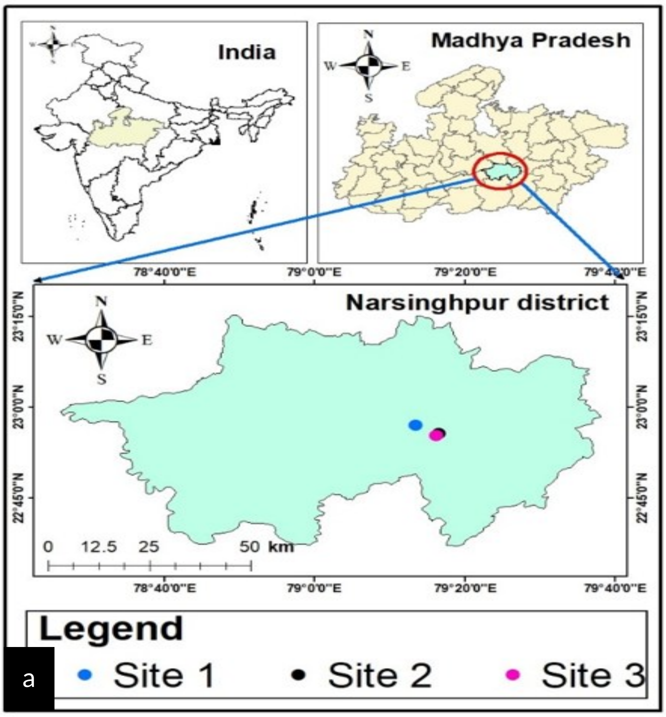

Figure 1. *Study area map. (a) study site locations, (b) sugarcane cultivation (c) Sugarcane residue and (d) photo during residue burning.*

Field sampling and soil sample collection

A Randomized Complete Block Design was employed to account for spatial variability in soil and management conditions. For study purpose, soil samples were collected from three different sites in Narsinghpur district. At each site, soil samples were taken at a depth of 0-15 cm from both of the pre-burned and post-burned sugarcane fields by using a soil corer. The post-burning soil samples were taken from the same field as the pre-burned samples within 48 hours following the burning of sugarcane residue. Five replicates were taken from each site for both before and after sugarcane residue burning. The soil samples were marked and immediately packed using air tight poly bags and brought to the laboratory for further analysis. In the laboratory, the soil samples were dried under sunlight. Thereafter, the soil samples were ground using a mortar and pestle and sieved through a 2 mm stainless steel sieve to ensure proper size and separate the coarse fragments. Subsequently, the five replicates were thoroughly mixed to make a composite mixture that served as a representative of a particular site and was used for further analysis.

Soil property analysis

Standard protocols were followed to analyze the various properties of the soil. The electrical conductivity (EC) was measured using an electrical conductivity meter, whereas the pH was measured using a pH meter. Similarly, the volumetric method (Walkley & Black, 1934) was used to determine soil organic carbon (SOC), whereas the Kjeldahl method (extracted with alkaline permanganate) (Subbiah & Asija, 1956), Olsen's method (Olsen, 1954) and flame photometric method (Toth & Prince, 1949) were used to determine available nitrogen (N), available phosphorus (P) and potassium (K) respectively. Additionally, Diethylene triamine pentaacetic acid extractant was used with the help of an atomic absorption spectrophotometer to determine the available Zinc (Zn), Copper (Cu), Iron (Fe) and Manganese (Mn).

Statistical analysis

Statistical analyses were performed to evaluate the impact of sugarcane residue burning on soil physico-chemical and nutrient parameters. Prior to analysis, the data were tested for normality using the Shapiro–Wilk test and for homogeneity of variances using Levene's test. A permutational multivariate analysis of variance (PERMANOVA) based on Bray–Curtis dissimilarities with 4,999 permutations was performed to examine the effect of burning on soil physico-chemical and nutrient characteristics. In addition, to identify which soil parameters contributed most to these differences, effect sizes were calculated using Cohen's d test. It represents the standardized mean difference between groups, providing a scale-independent measure of the strength of the burning effect on individual variables. The effect sizes were interpreted using commonly accepted thresholds i.e., values below 0.2 were considered negligible, 0.2-0.5 indicated a small effect, 0.5-0.8 a moderate effect, and values of 0.8 or higher represented a large effect. Further, to explore the multivariate relationships among soil physico-chemical and nutrient parameters and to identify the variables contributing most to variability, Principal Component Analysis (PCA) was performed. Prior to PCA, all variables were standardized to eliminate differences in measurement scales and to ensure that each variable contributed equally to the analysis. The PCA results were visualized using biplots, where both sample scores and variable loadings were plotted, allowing simultaneous assessment of sample clustering and variable contributions (Figure 2). This approach facilitated the identification of patterns associated with before-burning and after-burning soil samples. Statistical analyses and visualization were performed using ORIGIN PRO 2024.

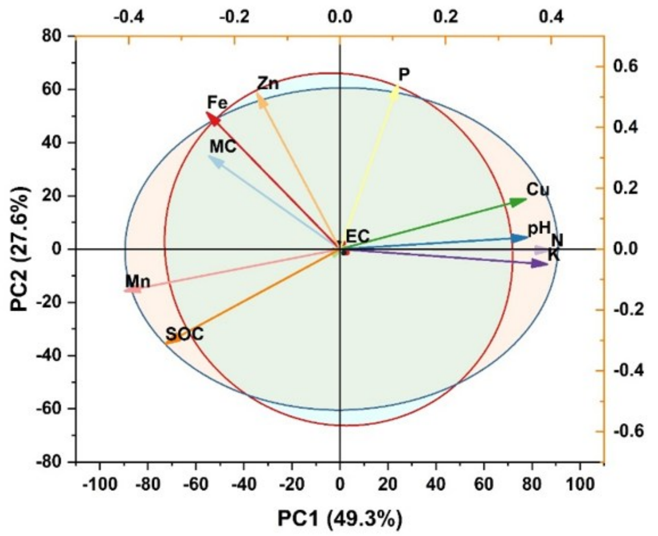

Figure 2. *Principal Component Analysis (PCA) biplot illustrating the relationships among soil physicochemical and nutrient parameters before (BB) and after burning (AB). Electrical conductivity (EC), Cupper (Cu), Manganese (Mn), Iron (Fe), Zinc (Zn), Soil organic carbon (SOC), Nitrogen (N), Potassium (K) and Phosphorous (P).*

RESULTS AND DISCUSSION

Effects of sugarcane residue burning on soil properties

The results of PERMANOVA analysis revealed no statistically significant difference between the before-burning and after-burning soils (pseudo-F = 2.65, R^2 = 0.40, p = 0.108). Although the burning treatment explained approximately 39.9% of the total multivariate variation, the difference was not significant at the p = 0.05 level. These results indicate that, overall, burning had a moderate but statistically non-significant influence on the overall soil properties, highlighting potential shifts in soil properties that could become more pronounced with larger sample sizes or repeated burning events.

Impact of sugarcane residue burning on soil physical and chemical properties

Assessment of the quality of soil through the quantification of various physio-chemical and biological properties acts as an important factor for the management and cultivation of different crops. In the present study, analysis of soil samples collected during the pre- and post-burning periods revealed significant changes in soil physical and chemical properties following on-field sugarcane residue burning. Before burning, soil pH across the study sites ranged from 7.69 to 8.26 with a mean value of 8.05 ± 0.18, whereas after burning, pH ranged from 8.02 to 8.26 with a mean value of 8.13 ± 0.07 (Table 1). The slight increase in soil pH after burning is consistent with previous studies on wheat and rice residue burning (Kaur *et al.*, 2019; Kumari *et al.*, 2023) and may be attributed to the deposition of ash enriched with base cations such as calcium, magnesium, potassium, and sodium released during combustion (Alcañiz *et al.*, 2018; Agbeshie *et al.*, 2022). In addition, the formation of oxides, hydroxides, and carbonates of sodium and potassium in the surface soil may further contribute to increased alkalinity (Ulery *et al.*, 1993). Similarly, EC in before-burning soil samples ranged from 82.57 to 129.03 µs/ppm with a mean value of 110.69 ± 14.27 µs/ppm, whereas after burning, EC increased substantially and ranged from 154.31 to 170.77 µs/ppm with a mean value of 163.09 ± 4.78 µs/ppm (Table 1). Overall, EC increased by 47.34% following residue burning. The increase in EC may be due to the release of soluble inorganic ions from burned soil organic matter (Verma *et al.*, 2019). Furthermore, collapse of soil aggregates and blockage of pore spaces by ash particles and dispersed ions may also contribute to elevated EC values after burning (Certini, 2005; Boerner *et al.*, 2009).

In contrast, soil MC decreased markedly after burning. Before burning, MC ranged from 18.42 to 50.86, whereas after burning it ranged from 14.68 to 36.67, showing an overall decline of 38.48%. The reduction in MC may be associated with the removal of surface residue cover and increased soil temperature after burning, which likely accelerated evaporation losses and reduced the water-holding capacity of soil. Cohen's *d* analysis further indicated that residue burning exerted varying levels of impact on different soil properties. EC showed a large effect size (d = −2.84), indicating that it was the most strongly affected soil parameter following burning. MC exhibited a moderate effect (d = 0.71), while pH showed only a small effect (d = −0.35). These findings suggest that sugarcane residue burning substantially altered soil ionic concentration and moisture conditions, while causing comparatively smaller changes in soil alkalinity.

Impact of sugarcane residue burning on soil organic carbon (SOC)

Before burning, SOC across the study sites ranged from 0.667 to 1.333%, whereas after burning it ranged from 0.951 to 1.480%. The mean SOC value in post-burned soil samples was 12.75% higher than in pre-burned samples (Table 1), indicating a positive influence of sugarcane residue burning on SOC content. Similar findings have been reported for wheat residue burning (Kumari *et al.*, 2023) and sugarcane residue burning (Blair, 2000). The increase in SOC following burning may be attributed to the formation of pyrogenic carbon during incomplete combustion of crop residues, addition of ash, and incorporation of partially burned biomass into the soil (Sánchez Meador *et al.*, 2017; Hu *et al.*, 2020; Agbeshie *et al.*, 2022; Pati *et al.*, 2025b). Such increases are generally associated with low-intensity fires (Dutta *et al.*, 2022). However, despite the observed increase (12.75%) in SOC, the gain was considerably lower than the organic matter content present in the sugarcane residues (40%) (Reddy & Chhabra, 2022), indicating that a substantial proportion of organic carbon was lost to the atmosphere during burning. Cohen's *d* analysis indicated a moderate effect size for SOC (d = -0.44), suggesting that residue burning moderately altered soil carbon status in the short term.

Impact of sugarcane residue burning on soil macronutrients (N, P, and K)

Micro and macro-nutrients are one of the important features of soil that have a significant influence on crop productivity and vegetation dynamics (Ganorkar *et al.*, 2017). The burning of sugarcane residues also influenced the macronutrient status of the soil. Before burning, N across study sites ranged from 50.18 to 62.72 Kg/ha, whereas after burning it ranged from 43.90 to 62.72 Kg/ha. Similarly, K ranged from 136.57 to 185.11 Kg/ha before burning and from 116.03 to 155.33 Kg/ha after burning. In contrast, P ranged from 12.44 to 36.67 Kg/ha before burning and from 12.28 to 38.16 Kg/ha after burning. The mean values of N and K decreased by 3.84% and 21.83%, respectively, whereas P increased by 7.95% in post-burned soil samples compared to pre-burned samples (Table 1).

The decline in N concentration after burning is consistent with previous studies on rice, wheat, and sugarcane residue burning (Souza *et al.*, 2012; Kumari *et al.*, 2023). It might be attributed to the losses from volatilization during biomass combustion (Certini, 2005; Caon *et al.*, 2014). The substantial reduction in K content observed in the present study contrasts with findings from rice and wheat residue burning studies (Kaur *et al.*, 2019; Kumari *et al.*, 2023), suggesting that sugarcane residue burning may exert differential effects on soil nutrient dynamics. On the other hand, the increase in available P after burning is in agreement with previous studies on sugarcane residue burning (Souza *et al.*, 2012). This increase may result from the mineralization of organic phosphorus into available forms during burning (Alcañiz *et al.*, 2016; Zhang & Biswas, 2017), as well as the addition of phosphorus-rich ash to the soil (Kumar *et al.*, 2019b). The formation of insoluble phosphorus compounds such as apatite in the presence of calcareous materials may also contribute to increased P concentration in post-burned soils (Agbeshie *et al.*, 2022). Previous studies have reported that residue burning can release nearly 80% of N, 25% of P, and 21% of K from crop residues (Mandal *et al.*, 2004; Dutta *et al.*, 2022). If incorporated back into the soil instead of being burned, crop residues could potentially contribute 30–35% of N and P and 70–80% of K to the soil nutrient pool (Reddy & Chhabra, 2022). Therefore, although post-burning soil samples in the present study showed slight increases in P, the concurrent reductions in N and K indicate potential long-term nutrient depletion under continuous residue burning practices. Cohen's *d* analysis showed a large effect for K (d = 1.31), small effect for N (d = 0.26), and negligible effect for P (d = −0.13), indicating that sugarcane residue burning exerted the strongest negative influence on potassium availability among the studied macronutrients.

Impact of sugarcane residue burning on soil micronutrients

Analysis of soil samples collected before and after on-field sugarcane residue burning revealed noticeable variations in soil micronutrient concentrations. Before burning, the values of Cu, Mn, Fe, and Zn across the study sites ranged from 1.74 to 2.03 µg/g, 9.06 to 10.16 µg/g, 12.89 to 14.40 µg/g, and 0.57 to 1.13 µg/g, respectively, with mean values of 1.92 ± 0.09 µg/g, 9.53 ± 0.32 µg/g, 13.74 ± 0.44 µg/g, and 0.86 ± 0.16 µg/g. After burning, Cu ranged from 1.63 to 1.80 µg/g with a mean of 1.73 ± 0.05 µg/g, Mn ranged from 9.49 to 10.38 µg/g with a mean of 9.79 ± 0.29 µg/g, Fe ranged from 13.10 to 14.53 µg/g with a mean of 13.94 ± 0.43 µg/g, and Zn ranged from 0.56 to 1.50 µg/g with a mean of 0.99 ± 0.27 µg/g. Overall, the mean values of Mn, Fe, and Zn increased by 2.73%, 0.01%, and 15.12%, respectively, whereas Cu decreased by 10.98% in post-burned soil samples compared to pre-burned samples (Table 1), indicating an overall positive influence of sugarcane residue burning on most soil micronutrients.
The increase in Mn, Fe, and Zn concentrations after burning may be associated with the deposition of ash and release of mineral elements from combusted plant residues, which temporarily enriches the soil nutrient pool. Similar responses of micronutrients following crop residue burning have also been reported for wheat residue burning (Kumari *et al.*, 2023). In contrast, the reduction in Cu concentration suggests that different micronutrients respond differently to burning intensity and post-fire soil conditions. Cohen's *d* analysis further demonstrated variable responses among micronutrients, with a large effect observed for Cu ($d = 1.50$), while Mn ($d = -0.49$), Fe ($d = -0.27$), and Zn ($d = -0.33$) exhibited small to moderate effects. These findings indicate that residue burning alters soil micronutrient dynamics unevenly across elements. Although the concentrations of several micronutrients increased immediately after burning, these nutrients may gradually decline over time due to leaching, erosion, and volatilization losses.

Study limitations

This study primarily focused on evaluating the influence of crop residue burning on soil physicochemical properties and nutrient dynamics. While these results provide meaningful insights, several limitations are acknowledged with respect to soil physical and biological assessments. Specifically, the study did not include measurements of bulk density and porosity, which are important for assessing structural stability and the soil's capacity to retain moisture following burning. Changes in these parameters could influence root growth, infiltration, and aeration factors that indirectly affect nutrient cycling and crop performance. Similarly, biological soil properties such as enzyme activities, soil microbial biomass and microbial N and P were not analyzed. These parameters are sensitive indicators of soil biological functioning and would provide a deeper understanding of the impacts of residue burning on microbial activity and nutrient mineralization. Future studies should integrate these physical and biological assessments to capture the full scope of residue burning effects on soil quality and sustainability. Incorporating such measurements would enhance the interpretability of results, allow stronger linkages between soil processes and crop performance, and contribute to more holistic soil management recommendations. Another limitation of this study is that it did not assess yield parameters and crop performance under the influence of crop residue burning. The study was conducted over a single season in natural field conditions, where farmers applied manures and fertilizers as part of regular management practices. These inputs introduce variability that could potentially bias yield data and confound the specific effects of residue burning. Therefore, addressing this question would require a controlled experimental design without supplementary inputs to isolate and accurately determine the impact of residue burning on crop performance. Future studies should employ long-term, controlled experiments without supplementary inputs to accurately evaluate the impact of residue burning on yield and crop performance across different crops and environmental conditions, thereby providing robust guidance for sustainable residue management.

Conclusion

This study evaluated the effects of on-field sugarcane residue burning on soil physical and chemical properties in agroecosystems of Central India. Results revealed that residue burning significantly altered soil properties, with a notable increase in pH, electrical conductivity, soil organic carbon, phosphorus, and certain micronutrients (Mn, Fe, Zn), while moisture content, nitrogen, potassium, and copper generally declined. Among all parameters, electrical conductivity and potassium showed the strongest responses to burning. In addition, comparative analysis with rice and wheat residue burning further indicated that such impacts are crop-specific, reflecting the inherent complexity of residue-soil interactions. Overall, the investigation indicates that residue burning leads to a short-term improvement in certain soil chemical properties, likely due to ash deposition, but also results in nutrient imbalances and losses of essential elements such as N, K, and Cu. Crop cultivation practices play a critical role in determining both the quantity and type of residues produced, as well as the extent of residue burning. In sugarcane systems, mechanized harvesting often leaves higher amounts of tops and trash in the field compared to manual harvesting, thereby increasing the potential for open-field burning. Additionally, crop management decisions, including fertilization regimes and irrigation practices, can affect residue moisture content and combustibility, further influencing burning intensity and frequency. These cultivation practices therefore directly affect the availability of residues for burning and their subsequent impact on soil physical and chemical properties. This emphasizes the need to integrate residue management considerations into overall crop production planning to sustain soil fertility and productivity. The findings of the present study highlight the transient nature of nutrient enrichment following burning and emphasize the need for long-term studies to assess its sustained effects on soil health. In addition, they strongly underscore the need for the adoption of innovative, environmentally sustainable residue management practices to safeguard soil health, improve crop productivity, and advance long-term agricultural sustainability.

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DECLARATIONS

Author contribution statement: Conceptualization: R.K., P.K.P. and P.K.K.; Methodology: R.K. and P.K.K.; Software and validation: P.K.P. and PK; Formal analysis and investigation: R.K. and P.K.P.; Resources: R.K.; Data curation: R.K. and P.K.P.; Writing—original draft preparation: R.K. and P.K.P.; Writing—review and editing: P.K.P., P.K. and M.L.K.; Visualization: P.K.; Supervision: M.L.K. and P.K.K.; Project administration: P.K.K. and M.L.K.; Funding acquisition: None. All authors have read and agreed to the published version of the manuscript.

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