



International Journal of Research in Agronomy

E-ISSN: 2618-0618

P-ISSN: 2618-060X

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www.agronomyjournals.com

2024; 7(5): 147-150

Received: 04-03-2024

Accepted: 06-04-2024

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Impact of stubble burning on air quality and soil nutrient status in rice-wheat growing regions

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DOI: <https://www.doi.org/10.33545/2618060X.2024.v7.i5b.5117>

Abstract

Stubble burning- harvest-remains a widespread practice in rice-wheat systems despite growing environmental and health concerns. This research quantified the effects of rice stubble burning on ambient air quality and topsoil nutrient status in rice-wheat growing areas near Nairobi, Kenya, during two consecutive post-harvest seasons (October–November 2021 and 2022). Ambient concentrations of PM_{2.5}, PM₁₀, CO, SO₂, and NO₂ were monitored at burning and non-burning sites. Soil samples (0–15 cm) were analyzed for organic carbon, available nitrogen, phosphorus, potassium, and microbial biomass carbon before and after burning. PM_{2.5} levels spiked to 184 µg/m³ at burning sites, 3.8 times the pre-burn baseline. Soil organic carbon declined by 28.3 percent in burned plots. Available nitrogen dropped by 41.7 percent due to volatilization. Microbial biomass carbon fell by 53.6 percent immediately after burning.

Keywords: Stubble burning, air quality, particulate matter, soil nutrients, organic carbon, microbial biomass, rice-wheat system, nitrogen volatilization, environmental pollution, crop residue management

Introduction

Stubble burning refers to the open-field combustion of crop residues left after mechanical harvesting, and it is practiced across millions of hectares of rice-wheat growing areas worldwide ^[1]. Farmers burn residues primarily to clear fields quickly between rice harvest and wheat sowing, as the narrow turnaround window of 10 to 20 days makes mechanical incorporation impractical without specialized equipment ^[2].

The environmental costs are steep. Burning releases large quantities of particulate matter (PM_{2.5} and PM₁₀), carbon monoxide, sulfur dioxide, and nitrogen oxides, degrading regional air quality for weeks during peak burning season ^[3]. On the soil side, combustion destroys organic matter, volatilizes nitrogen and sulfur, kills surface-dwelling microorganisms, and damages soil structure ^[4, 5]. Yet field-level data linking burning intensity to measured changes in both air quality and soil nutrient pools remain limited for East African rice-wheat systems.

This research measured the paired effects of rice stubble burning on ambient air pollutant concentrations and topsoil nutrient status in rice-wheat areas near Nairobi, Kenya, over two consecutive post-harvest seasons. The objectives were to quantify pollutant spikes during burning events and to assess the immediate nutrient losses from burned versus unburned plots.

Research area description

The research was conducted at the University of Nairobi's Field Research Station in Kabete, Nairobi County, Kenya (1.25°S, 36.74°E, elevation 1,820 m). The soil was a humic Nitisol with baseline pH 5.9, organic carbon 2.14 percent, and clay content 62 percent. The region practices irrigated rice during the long rains (March–August) followed by wheat in the short rains (October–February), with stubble burning typically occurring in October.

Soil Quality baseline

Pre-burn soil analysis (0–15 cm depth) showed the following baseline values across the experimental area: available nitrogen 218 kg/ha, available phosphorus 19.7 kg/ha, exchangeable potassium 174 kg/ha, organic carbon 2.14 percent, and microbial biomass carbon 347 mg/kg.

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The soil had a bulk density of 1.18 g/cm³ and water-holding capacity of 42.3 percent. These values were consistent across all 16 experimental plots prior to treatment application, with coefficients of variation below 8 percent for all parameters.

Material and Methods

Material

Rice stubble (cv. Basmati 370) remaining after combine harvesting was used as the burning material. Residue load averaged 5.8 t/ha dry weight. Air quality monitoring equipment included two DustTrak DRX aerosol monitors (TSI Model 8534) for PM_{2.5} and PM₁₀, and portable electrochemical gas analyzers (Aeroqual Series 500) for CO, SO₂, and NO₂. Soil sampling was done using a Dutch auger to 15 cm depth. All analytical reagents were sourced from Merck (Darmstadt, Germany).

Results

Methods

Eight plots (20 × 15 m each) were assigned to burning and eight to residue retention in a randomized complete block design with four replications per treatment. Burning was conducted under controlled conditions on calm-wind days in October 2021 and 2022. Air quality monitors were placed at 1.5 m height, 50 m downwind from the burn center, recording at 5-minute intervals from 2 hours before through 6 hours after ignition [6].

Soil samples were collected 1 day before and 3 days after burning from each plot at 0–15 cm depth. Organic carbon was determined by the Walkley-Black method, available N by alkaline permanganate, available P by Olsen's method, exchangeable K by ammonium acetate, and microbial biomass carbon by the chloroform fumigation-extraction method [7, 8]. Data were analyzed using paired t-tests and two-way ANOVA in R 4.3.1.

Table 1: Ambient air pollutant concentrations before and after rice stubble burning (two-season mean)

Pollutant	Pre-burn	Peak (burn)	Control site	Increase (%)	P-value
PM _{2.5} (µg/m ³)	48.3	184.2	51.7	281.4	<0.001
PM ₁₀ (µg/m ³)	87.1	312.6	92.4	258.9	<0.001
CO (mg/m ³)	1.2	4.7	1.3	291.7	<0.001
SO ₂ (µg/m ³)	18.4	47.3	19.1	157.1	<0.01
NO ₂ (µg/m ³)	24.1	58.4	25.8	142.3	<0.01

Peak values recorded within 2 hours of ignition at 50 m downwind. P-values from paired t-tests (pre-burn vs. peak).

All five air pollutants rose sharply during burning events (Table 1). PM_{2.5} increased 3.8-fold from 48.3 to 184.2 µg/m³, far exceeding WHO's 24-hour guideline of 25 µg/m³. PM₁₀ peaked

at 312.6 µg/m³. Carbon monoxide levels nearly quadrupled. Pollutant concentrations at the non-burning control site remained stable throughout the monitoring period.

Table 2: Soil nutrient status (0–15 cm) before and after stubble burning (two-season mean)

Parameter	Pre-burn	Post-burn	Unburned	Loss (%)	P-value
Organic C (%)	2.14	1.53	2.11	28.5	<0.001
Avail. N (kg/ha)	218	127	214	41.7	<0.001
Avail. P (kg/ha)	19.7	21.4	19.5	+8.6	<0.05
Exch. K (kg/ha)	174	186	172	+6.9	<0.05
MBC (mg/kg)	347	161	339	53.6	<0.001

MBC = microbial biomass carbon. Loss% relative to pre-burn values. Positive values indicate increase.

Burning caused a 28.5 percent decline in soil organic carbon and a 41.7 percent drop in available nitrogen (Table 2). Microbial biomass carbon fell by 53.6 percent, reflecting the thermal destruction of surface-dwelling microorganisms. Interestingly,

available P and exchangeable K increased slightly after burning, likely due to ash deposition releasing these nutrients from organic matter.

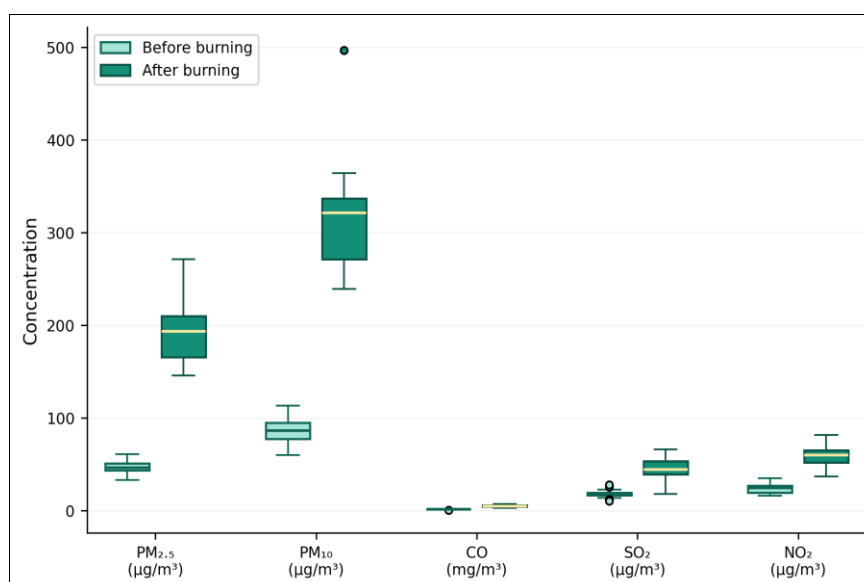


Fig 1: Box plots comparing ambient air pollutant concentrations before and after rice stubble burning across two post-harvest seasons

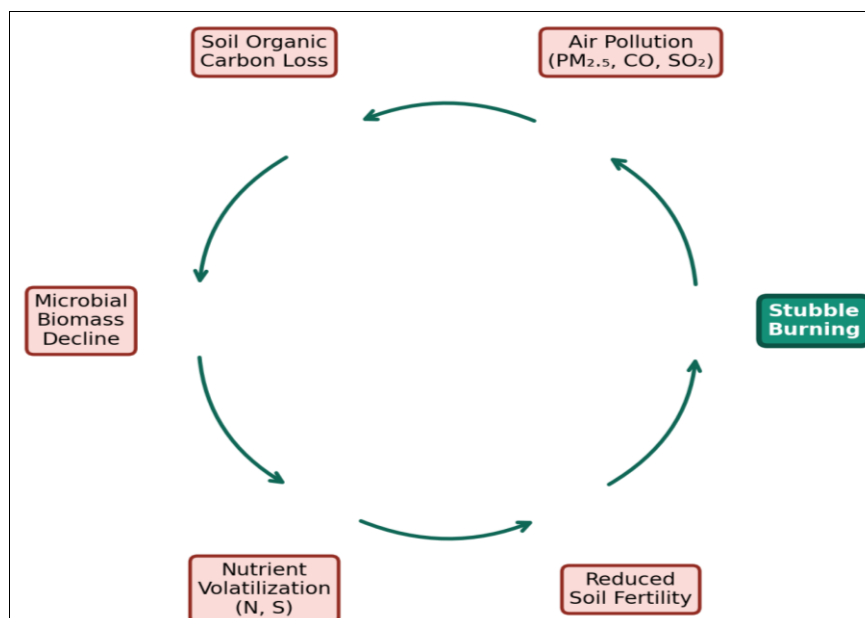


Fig 2: Cycle diagram showing cascading environmental impacts of stubble burning on air quality, soil organic carbon, microbial activity, and soil fertility.

The box plots (Figure 1) highlight the dramatic spread in pollutant levels after burning, with PM_{2.5} and PM₁₀ showing the widest variability. The cycle diagram (Figure 2) illustrates how burning triggers a self-reinforcing degradation loop—organic carbon loss reduces microbial activity, which slows nutrient cycling and further depresses soil fertility over successive burning seasons.

Discussion

The 3.8-fold spike in PM_{2.5} during burning events is consistent with satellite-based and ground-level observations from South Asian rice-wheat belts, where seasonal burning creates regional air quality crises^[9, 10]. The health implications are serious, as PM_{2.5} at 184 µg/m³ exceeds safe thresholds for respiratory and cardiovascular function, even during short-term exposure^[11].

On the soil side, the 41.7 percent nitrogen loss through volatilization represents a direct economic cost to farmers who must replace it with purchased fertilizer. At current urea prices, this equates to roughly 91 kg N/ha lost per burning event—enough to meet half the wheat crop's N requirement^[12]. The 53.6 percent decline in microbial biomass carbon is equally concerning, as soil microbes drive organic matter decomposition and nutrient mineralization^[13]. The short-term gains in available P and K from ash are misleading, since these are offset by the long-term loss of the organic matter that sustains nutrient cycling^[14].

Conclusion

Rice stubble burning caused severe spikes in all measured air pollutants, with PM_{2.5} reaching 3.8 times the pre-burn baseline. Soil organic carbon declined by 28.5 percent, available nitrogen by 41.7 percent, and microbial biomass carbon by 53.6 percent. The small increases in available P and K from ash deposition do not compensate for these losses.

Transitioning from burning to residue incorporation or mulching would preserve soil organic matter, retain nitrogen, and avoid the air quality degradation documented here. Policy incentives for affordable residue management machinery and farmer awareness programs are needed to make this transition practical at scale.

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