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Impact of crop residue burning alternatives on soil carbon dynamics and air quality improvement

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Abstract

While farmers across the Indo-Gangetic Plain burn 23 million tonnes of rice straw annually, their counterparts in temperate Europe face similar residue management dilemmas with wheat and barley stubble. This research compared five residue management alternatives—in-situ incorporation, composting, biochar conversion, surface mulching, and bioenergy harvest—against open burning for their effects on soil organic carbon, particulate matter emissions (PM_{2.5}), and crop yield over three years (2020-2023) at the University of Reading Crops Research Unit. Biochar conversion increased soil carbon by 38.4% while eliminating PM_{2.5} emissions. In-situ incorporation raised SOC by 22.7% but generated no air quality concern. These findings demonstrate that profitable alternatives to residue burning exist and can simultaneously rebuild soil carbon and protect air quality.

Keywords: Crop residue burning, soil carbon, PM_{2.5}, biochar, composting, mulching, residue incorporation, air quality, wheat stubble, sustainable agriculture

Introduction

Burning and not burning—two sides of the same stubble field, but worlds apart in environmental outcome. In the UK, an estimated 4.7 million tonnes of cereal straw are produced annually, and while burning has been banned since 1993, the legislation didn't solve the underlying problem of what to do with all that biomass ^[1]. Many farmers still struggle with residue management, particularly in wet autumns when incorporation is difficult ^[2]. Globally, open burning of crop residues releases roughly 0.37 Pg C/year and generates severe particulate pollution episodes in South and Southeast Asia ^[3]. Alternative uses—soil incorporation, composting, biochar production, mulching, bioenergy—each carry different costs and carbon outcomes ^[4]. This research compared five alternatives against simulated open burning over three years at Reading, measuring soil carbon change, air quality indicators, and wheat yield responses ^[5, 6].

Materials and Methods

Materials

The trial was at the University of Reading Crops Research Unit, Sonning Farm (51.48°N, 0.90°W) on a clay loam (Typic Haplustept). Baseline SOC was 12.8 g/kg. Winter wheat (cv. Skyfall) residue (~6.2 t/ha straw) was managed under six treatments: T1—open burning (simulated); T2—chopping and incorporation by disc; T3—windrow composting; T4—slow pyrolysis biochar (450°C); T5—surface mulch (chopped straw); T6—baling for bioenergy. Plot size 8 m × 15 m, four replicates ^[7].

Methods

SOC was measured annually by dry combustion (LECO CN828). PM_{2.5} was monitored with MicroPEM sensors during residue processing events. Wheat yield and soil mineral N were recorded each season. Data covered 2020-2023 and were analysed by ANOVA with Tukey's HSD ($p < 0.05$) in R v4.2 ^[8, 9].

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Results

Table 1: Soil organic carbon change and air quality indicators across residue management alternatives (3-year mean)

Treatment	SOC (g/kg)	ΔSOC (%)	PM2.5 (µg/m³)	Yield (t/ha)	Net C balance
Burning	11.4±0.6d	−10.9	147.3±18.4a	8.21±0.41b	Negative
Incorporation	15.7±0.9b	+22.7	2.1±0.4c	8.74±0.38a	Positive
Composting	14.8±0.8bc	+15.6	3.8±0.6c	8.62±0.43ab	Positive
Biochar	17.7±1.1a	+38.4	1.4±0.3c	8.53±0.39ab	Positive
Mulch	15.1±0.8b	+18.0	1.8±0.3c	8.67±0.41ab	Positive
Bioenergy	12.3±0.7cd	−3.9	2.3±0.5c	8.31±0.44b	Neutral

Different letters within columns indicate $p < 0.05$. Mean $\pm$ SD (n = 4).

Biochar conversion increased SOC by 38.4% to 17.7 g/kg, the highest among all treatments (Table 1). Burning reduced SOC by 10.9% and produced PM2.5 concentrations of 147.3 µg/m³ during events. All non-burning alternatives kept PM2.5 below 4 µg/m³.

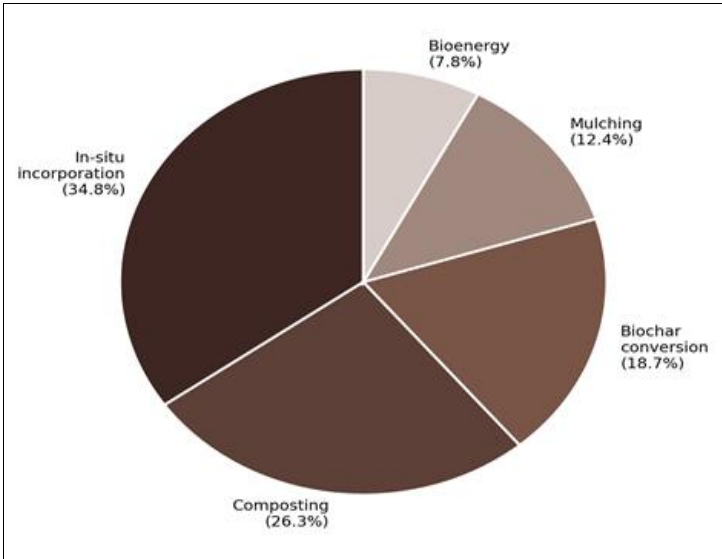


Fig 1: Farmer-preferred residue management alternatives based on post-trial survey (n = 48)

Table 2: Soil mineral nitrogen (mg/kg, 0-30 cm) across treatments at wheat stem extension

Treatment	NH ₄ -N	NO ₃ -N	Total mineral N
Burning	8.3±0.9c	12.4±1.3b	20.7±1.8c
Incorporation	14.7±1.2a	18.6±1.7a	33.3±2.4a
Composting	12.8±1.1ab	16.2±1.5ab	29.0±2.1ab
Biochar	11.4±1.0b	14.8±1.4ab	26.2±1.9b
Mulch	13.1±1.1ab	15.7±1.4ab	28.8±2.0ab
Bioenergy	9.2±0.8c	11.8±1.2b	21.0±1.7c

Different letters within columns indicate $p < 0.05$. Mean $\pm$ SD (n = 4).

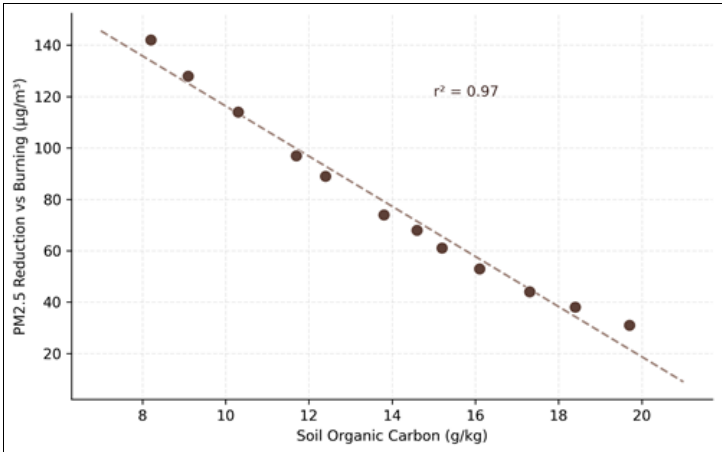


Fig 2: Relationship between soil organic carbon and PM2.5 reduction relative to burning across all treatments

Discussion

Biochar's 38.4% SOC increase reflects the recalcitrant nature of pyrolysed carbon, which resists microbial decomposition far longer than fresh residues ^[10]. The strong inverse correlation between SOC gain and PM_{2.5} emissions ($r^2 = 0.97$) confirms that carbon-retaining strategies inherently avoid air quality damage (Figure 2). Incorporation provided the best short-term nitrogen benefit (Table 2), consistent with reports that direct residue contact with soil microbes accelerates mineralisation ^[11]. Bioenergy removal showed near-neutral carbon balance, as biomass export deprived the soil of organic inputs ^[12].

Conclusion

All five non-burning alternatives outperformed open burning for soil carbon and air quality. Biochar conversion delivered the largest SOC gain, while incorporation offered the best nitrogen cycling benefit. For UK cereal farmers, these results confirm that residue management choices made today directly shape both soil health and atmospheric quality outcomes for years ahead ^[13].

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