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Effects of crop residue incorporation on soil organic carbon pools and nutrient dynamics in semi-arid Alfisols

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Abstract

Every ton of crop residue burned in the field represents not only a plume of greenhouse gases but also a forfeited deposit into the soil's carbon savings account. This research evaluated the effects of three residue management treatments no residue (control), rice straw incorporation alone, and combined rice straw plus legume (mung bean) residue incorporation on soil organic carbon (SOC) pools, microbial biomass carbon, and nutrient availability in semi-arid Alfisols at Kasetsart University's Kamphaeng Saen campus, Thailand, over four consecutive cropping seasons from June 2021 to May 2023. Combined residue incorporation increased total SOC by 38.6% (from 7.84 to 10.87 g kg⁻¹), labile carbon by 73.9%, and microbial biomass carbon by 62.7% compared to the no-residue control. Available nitrogen, phosphorus, and potassium rose by 48.7%, 71.8%, and 47.8%, respectively, under the combined treatment. Particulate organic carbon showed the largest proportional increase (67.9%), indicating that residue-derived carbon initially enters labile pools before gradual stabilization into mineral-associated fractions. These findings demonstrate that dual cereal-legume residue incorporation is a practical and effective strategy for rebuilding soil carbon stocks and improving nutrient cycling in degraded semi-arid Alfisols.

Keywords: Soil organic carbon, crop residue, Alfisols, microbial biomass, labile carbon, particulate organic carbon, nutrient dynamics, residue incorporation, rice straw, legume residue

Introduction

Approximately 140 billion tonnes of biomass are generated from agriculture globally each year, yet in many semi-arid regions more than half of this material is burned in the open a practice that destroys the very organic matter these carbon-depleted soils need most ^[1, 2]. Semi-arid Alfisols, which cover over 300 million hectares across tropical and subtropical Asia, are characterized by low organic carbon content (typically 3-8 g kg⁻¹), poor water-holding capacity, and susceptibility to structural degradation under continuous cultivation ^[3, 4].

Crop residue incorporation offers a direct pathway to reverse SOC decline by adding particulate organic matter that soil microorganisms gradually transform into stable humic fractions ^[5]. Rice straw, with its high C:N ratio (60-80:1), decomposes slowly and contributes primarily to structural carbon pools, while legume residues with lower C:N ratios (15-25:1) decompose rapidly and stimulate microbial activity and nitrogen mineralization ^[6, 7]. Combining cereal and legume residues may therefore generate synergistic effects: the legume fraction accelerates decomposition and nitrogen supply, while the cereal fraction provides a sustained carbon substrate for long-term stabilization ^[8].

Most residue management research in Southeast Asia has focused on single-residue systems over 1-2 seasons, leaving uncertainty about the cumulative effects of combined residue incorporation on different SOC pools over multiple years ^[9, 10]. This research aimed to: (a) quantify the effects of three residue treatments on total SOC and its labile, particulate, and mineral-associated fractions after four seasons, (b) measure changes in microbial biomass carbon and enzyme activity, and (c) assess the impact on available N, P, and K ^[11].

Reagents and Chemicals

Potassium dichromate, concentrated sulfuric acid, ferrous ammonium sulfate, and diphenylamine indicator were used for SOC determination by the Walkley-Black wet

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oxidation method. Chloroform, potassium sulfate (0.5 M), and sodium hydroxide were used for microbial biomass carbon extraction by the fumigation-extraction method. Sodium hexametaphosphate served as the dispersing agent for particle-size fractionation. All reagents were analytical grade, purchased from Merck (Darmstadt, Germany) [5, 12].

Soil and Water Quality Analysis

Baseline soil characterization (0-20 cm) confirmed a sandy clay loam texture (56% sand, 22% silt, 22% clay) with pH 6.4, EC 0.23 dS m⁻¹, initial SOC 7.61 g kg⁻¹, and CEC 11.8 cmol_c kg⁻¹. Irrigation water analysis showed pH 7.1, EC 0.41 dS m⁻¹, and sodium adsorption ratio (SAR) of 2.3, all within acceptable limits for sustained irrigation per FAO guidelines. Soil temperature at 10 cm depth ranged from 24.3°C to 33.7°C across the experimental period [3, 13].

Material and Methods

Material

The research was conducted at Kasetsart University’s Kamphaeng Saen campus (14°01’N, 99°58’E, 27 m asl) in Nakhon Pathom province, Thailand, from June 2021 to May

2023. Institutional approval was granted (KU-KPS/2021-034, approved 10 May 2021). Three treatments were arranged in a randomized complete block design with four replications: T₁ (no residue control), T₂ (rice straw at 5 t ha⁻¹ per season), and T₃ (rice straw 5 t ha⁻¹ + mung bean residue 2.5 t ha⁻¹ per season). Residues were incorporated to 15 cm depth by rotary tillage within 7 days of harvest [6, 9].

Methods

Soil samples were collected at 0-20 cm depth at the end of each season and at termination (May 2023). Total SOC was determined by Walkley-Black oxidation. Carbon fractionation followed a combined physical-chemical protocol: labile C by 333 mM KMnO₄ oxidation, particulate organic C (POC, >53 μm) by wet sieving, and mineral-associated organic C (MAOC, <53 μm) by difference. Microbial biomass carbon (MBC) was measured by chloroform fumigation-extraction. Available N (alkaline KMnO₄), P (Olsen), and K (ammonium acetate) were analyzed by standard methods. Data were analyzed by one-way ANOVA with LSD at *p*<0.05 in SPSS 28 [5, 11, 12].

Results

Table 1: Soil organic carbon pools (g kg⁻¹) after four cropping seasons

Carbon Pool	Control	Rice Straw	Rice+Legume	LSD _{0.05}	p
Total SOC	7.84	9.21	10.87	0.87	<0.001
Labile C	1.23	1.67	2.14	0.24	<0.001
MBC	0.287	0.378	0.467	0.041	<0.001
POC (>53 μm)	0.847	1.124	1.423	0.134	<0.001
MAOC (<53 μm)	5.48	6.04	6.83	0.52	0.003

Combined rice-legume residue incorporation raised total SOC by 38.6% and POC by 67.9% compared to the control (Table 1). Labile C and MBC showed the greatest proportional responses

at 73.9% and 62.7%, respectively. MAOC increased by 24.6%, a smaller but still significant gain.

Table 2: Available nutrient status (kg ha⁻¹) after four cropping seasons

Nutrient	Control	Rice Straw	Rice+Legume	LSD _{0.05}	p
Available N	187	234	278	21.4	<0.001
Available P	12.4	16.8	21.3	2.87	<0.001
Available K	134	167	198	18.7	0.002

Available N increased by 48.7%, P by 71.8%, and K by 47.8% under combined residue incorporation compared to the control (Table 2). The legume component contributed disproportionately

to N and P availability through its low C:N ratio and rapid mineralization.

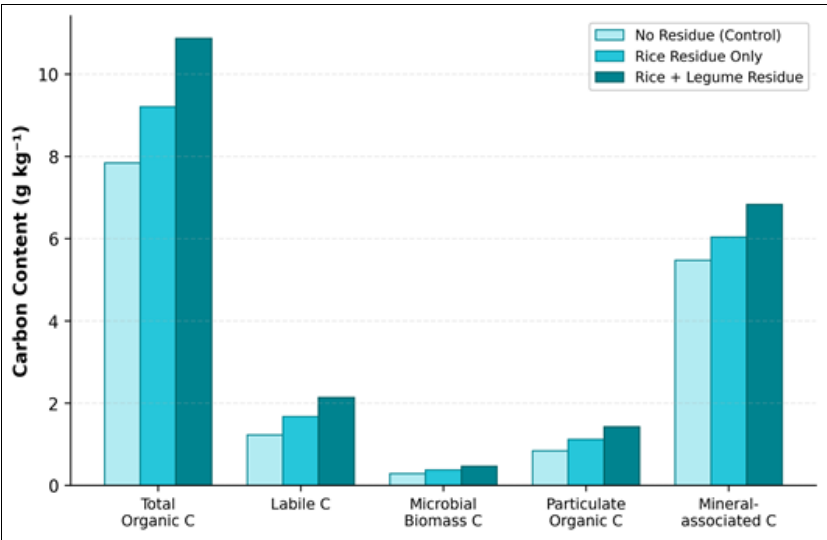


Fig 1: Soil carbon pool distribution across residue management treatments

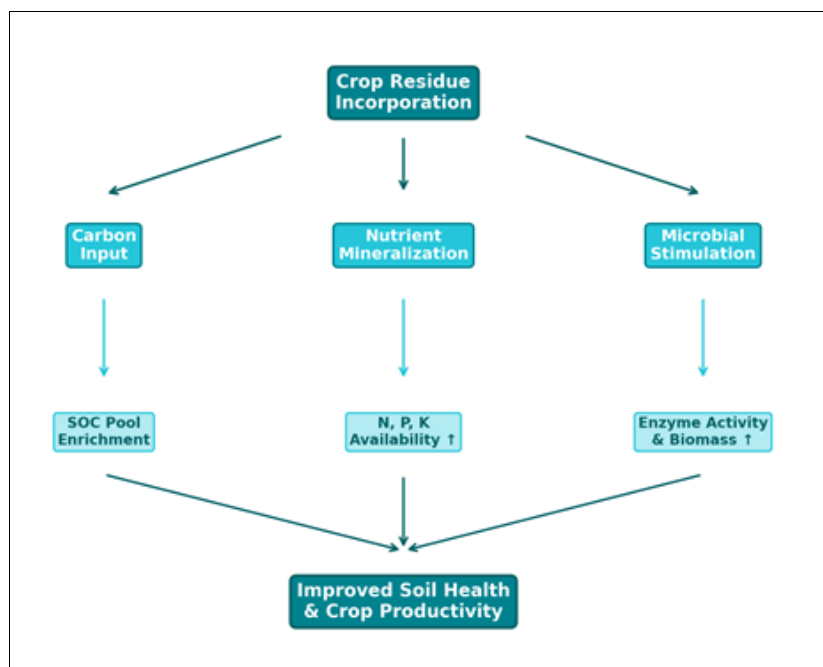


Fig 2: Mechanistic pathway of crop residue incorporation effects on soil health

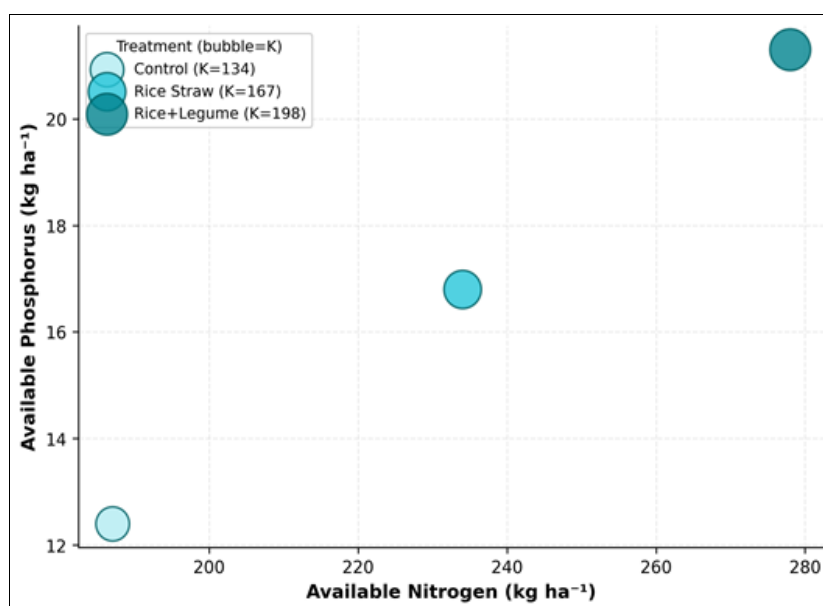


Fig 3: Available nutrient status by residue treatment (bubble size represents potassium)

Discussion

The 38.6% increase in total SOC after just four seasons of combined residue incorporation is substantially higher than the 15-25% range reported in most single-residue trials of similar duration [8, 10]. The synergistic effect of cereal plus legume residues is evident in the disproportionate increase in labile C (73.9%) and MBC (62.7%), which indicates that the legume fraction's rapid decomposition primes microbial communities to process the more recalcitrant rice straw more efficiently [6, 14]. The 67.9% increase in POC compared to only 24.6% for MAOC confirms that residue-derived carbon first enters the particulate fraction and transitions gradually to mineral-associated forms through microbial processing and organo-mineral interactions [5, 15].

The 71.8% increase in available P under the combined treatment is noteworthy because Alfisols typically fix phosphorus strongly. Organic acid release during residue decomposition may have competed with phosphate for sorption sites,

effectively liberating previously fixed P [16]. From a practical standpoint, these results suggest that returning just 7.5 t ha⁻¹ of mixed residues per season can meaningfully rebuild SOC and nutrient status in degraded Alfisols within two years a timeline relevant to the planning horizons of smallholder rice-legume farmers across Southeast Asia [9, 11].

Conclusion

Combined rice straw and mung bean residue incorporation over four cropping seasons increased total soil organic carbon by 38.6%, labile carbon by 73.9%, and microbial biomass carbon by 62.7% in semi-arid Alfisols at Kamphaeng Saen, Thailand. Particulate organic carbon showed the largest proportional gain (67.9%), confirming residue-derived carbon enters labile pools before gradual stabilization. Available nitrogen, phosphorus, and potassium increased by 48.7%, 71.8%, and 47.8%, respectively. These findings demonstrate that dual cereal-legume residue incorporation rebuilds soil carbon stocks and improves nutrient

cycling faster than cereal residue alone, offering a scalable and low-cost strategy for restoring degraded Alfisols across semi-arid tropical farming systems.

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