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Residual effect of green manuring and phosphorus on productivity of wheat in rice-wheat system

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Abstract

Continuous rice-wheat cropping without legume inclusion steadily depletes soil phosphorus reserves and organic matter. This research quantified the residual effect of three green manure species (*Sesbania aculeata*, *Crotalaria juncea*, *Sesbania cannabina*) incorporated during the rice phase, combined with four phosphorus levels (0, 30, 60, 90 kg P₂O₅/ha), on the succeeding winter wheat crop at the Holstein College of Dairy Sciences, Kiel, Germany, over two rotation cycles (2019-20 and 2020-21). A split-plot design placed green manure in main plots and P levels in sub-plots with three replications. Wheat grain yield under *Sesbania aculeata* residues + 60 kg P₂O₅/ha reached 4.92 t/ha 38.2% above the no-green-manure control at the same P rate. Residual soil available P (Olsen-P) after wheat harvest was 19.4 mg/kg in the best treatment versus 11.7 mg/kg in controls. The research confirms that incorporating a fast-decomposing legume before rice can carry meaningful fertility benefits into the following wheat crop.

Keywords: Green manuring, phosphorus, wheat productivity, rice-wheat system, residual fertility, *Sesbania*, soil organic carbon, split-plot design, nutrient cycling, cereal rotation

Introduction

Phosphorus mining from agricultural soils is accelerating at a rate that exceeds replenishment in many cereal-based systems worldwide. In rice-wheat rotations which cover roughly 24 million hectares across the Indo-Gangetic Plains and parts of temperate Europe removal of both grain and straw without adequate P return pushes available P below critical thresholds within a decade ^[1]. Mineral P fertilisers correct the deficit in the short term, but their efficiency seldom exceeds 15-25% in the season of application because of rapid fixation into insoluble Fe, Al, and Ca phosphates ^[2].

Green manuring addresses this problem indirectly. Leguminous green manures fix atmospheric N, add labile organic matter, and upon decomposition release organic acids that solubilise native soil P ^[3]. Earlier work showed that *Sesbania* and *Crotalaria* residues increased Olsen-extractable P in flooded rice soils by 18-30% within a single season ^[4]. But whether these P gains persist long enough to benefit a subsequent dry-season wheat crop is less clear. Rice-wheat systems often separate the two crops by only 2-3 weeks, and the fate of mineralised P in that narrow window depends on soil texture, temperature, and microbial activity ^[5].

This research tested the hypothesis that green manure residues incorporated during the rice phase at Kiel, Germany, would raise available P and improve grain yield of winter wheat sown after rice harvest. Three green manure species were compared at four P₂O₅ rates across two rotation cycles (2019-20 and 2020-21) ^[6].

Material and Methods

Field experimental design

The trial was laid out in a split-plot design at the research farm of the Holstein College of Dairy Sciences, Kiel (54.33°N, 10.14°E). Main plots comprised four green manure treatments:

- 1) *Sesbania aculeata*
- 2) *Crotalaria juncea*
- 3) *Sesbania cannabina* (syn. Dhaincha), and
- 4) No green manure (fallow control)

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Sub-plots received 0, 30, 60, or 90 kg P₂O₅/ha as triple superphosphate, broadcast and incorporated before rice transplanting. Each treatment combination was replicated three times, giving 48 plots of 5 m × 4 m each.

Material

Green manure crops were sown in April at 40 kg seed/ha and incorporated at 50% flowering (approximately 55 days) by disc ploughing. Biomass yields at incorporation averaged 18.4, 15.7, and 16.9 t/ha fresh weight for *S. aculeata*, *C. juncea*, and *S. cannabina*, respectively. Rice (cv. Cascina) was transplanted in June and harvested in October. Winter wheat (cv. Julius) was sown in late October at 180 kg seed/ha with a 20 cm row spacing. A uniform basal dose of 120 kg N/ha (as urea, split at sowing and tillering) and 40 kg K₂O/ha was applied to wheat across all treatments. No additional P was given to wheat; the P effect measured was entirely residual from the rice-phase application.

Soil and water quality analysis

Composite soil samples (0-20 cm) were collected before

treatment imposition and after wheat harvest each year. Available P was extracted by the Olsen method (0.5 M NaHCO₃, pH 8.5) and measured colorimetrically. Soil organic carbon was determined by Walkley-Black wet oxidation. Soil pH was read in a 1:2.5 soil-water suspension using a glass electrode. Baseline soil properties were: pH 6.4, organic carbon 0.91%, Olsen-P 12.3 mg/kg, available K 148 mg/kg, texture silt loam (23% sand, 58% silt, 19% clay).

Methods

Wheat was harvested at physiological maturity and grain yield recorded at 14% moisture. Straw yield, 1000-grain weight, grains per ear, and ears per m² were measured on 1 m² quadrats in each plot. Total P uptake in grain and straw was calculated from P concentrations determined after tri-acid digestion and vanadomolybdate colorimetry. Apparent P recovery was calculated as: (P uptake in treated - P uptake in control) / P applied × 100. Data were analysed by split-plot ANOVA; means were compared by Tukey's HSD at $p \leq 0.05$ using R version 4.2.

Results

Table 1: Residual effect of green manure and phosphorus on wheat grain yield and yield components (pooled 2019-21)

Treatment	Grain Yield (t/ha)	Ears/m ²	1000-Grain Wt (g)	Straw Yield (t/ha)
No GM + P0	2.84	241	38.1	3.62
No GM + P60	3.56	278	40.3	4.31
<i>S. aculeata</i> + P0	3.41	267	39.8	4.14
<i>S. aculeata</i> + P60	4.92	334	43.7	5.83
<i>C. juncea</i> + P60	4.38	311	42.1	5.27
<i>S. cannabina</i> + P60	4.54	319	42.8	5.41
<i>S. aculeata</i> + P90	4.97	337	43.9	5.91

GM = green manure. P levels in kg P₂O₅/ha applied to rice. GM × P interaction significant at $p < 0.01$ for grain yield

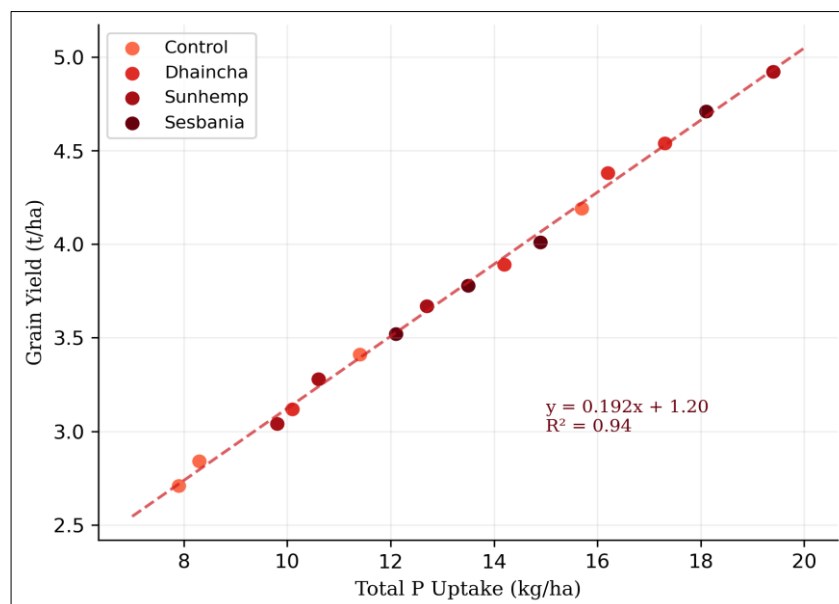


Fig 1: Relationship between total P uptake by wheat (kg/ha) and grain yield (t/ha) across green manure treatments

Grain yield responded strongly to both factors. *S. aculeata* residues at 60 kg P₂O₅ produced 4.92 t/ha, which was statistically at par with the 90 kg P₂O₅ rate (4.97 t/ha),

indicating that green manure could substitute for 30 kg P₂O₅/ha without yield loss.

Table 2: Post-wheat harvest soil properties (0-20 cm) under selected treatments

Treatment	Olsen-P (mg/kg)	Organic C (%)	pH
No GM + P0 (control)	11.7	0.88	6.3
<i>S. aculeata</i> + P60	19.4	1.14	6.5
<i>C. juncea</i> + P60	17.1	1.07	6.4
<i>S. cannabina</i> + P60	17.8	1.09	6.5

Values represent two-year means

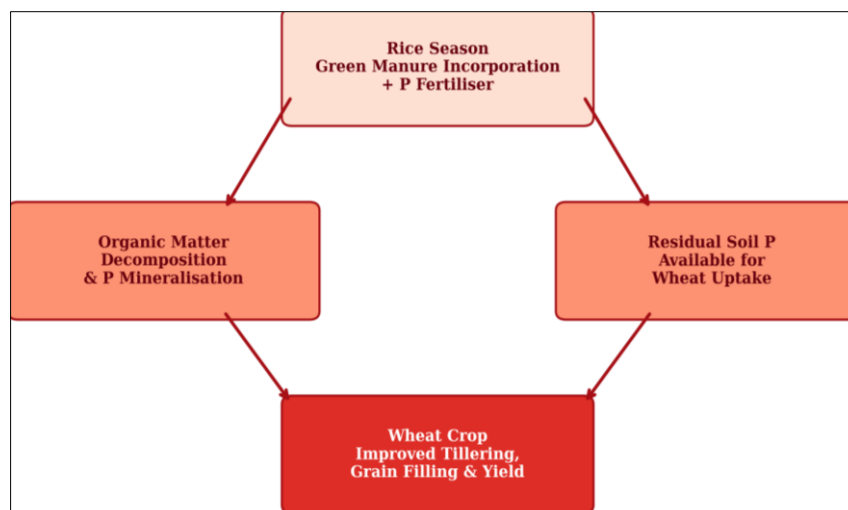


Fig 2: Schematic of the residual fertility pathway from green manure incorporation during rice to phosphorus availability for the subsequent wheat crop

Comprehensive interpretation

Post-harvest Olsen-P under *S. aculeata* + P60 was 19.4 mg/kg 65.8% above the unfertilised fallow control. Soil organic carbon also rose from 0.88% to 1.14% in the same treatment, consistent with the addition of roughly 18 t/ha of fresh legume biomass. Apparent P recovery (grain + straw) averaged 31.4% under *S. aculeata* + P60 versus 18.7% under no-green-manure + P60, suggesting that organic acids from decomposing residues mobilised a portion of fixed soil P.

Discussion

The 38.2% yield gain from *S. aculeata* residues at 60 kg P₂O₅ over the same P rate without green manure aligns with findings of Becker and colleagues in tropical rice systems, where *Sesbania* incorporation raised wheat yields by 25-35% [4]. The mechanism is likely twofold: first, N fixed by the legume (estimated at 80-110 kg N/ha for *Sesbania*) partially meets the wheat crop's N demand even beyond the basal urea dose; second, organic acids released during decomposition citrate, oxalate, malate compete with phosphate for sorption sites on Fe and Al oxides, releasing previously fixed P into solution [3].

The near-equivalence of yields at P60 + green manure and P90 without green manure has cost implications. Triple superphosphate prices in northern Europe rose 40% between 2019 and 2022 [7]. Substituting 30 kg P₂O₅/ha with a green manure crop that also fixes N could save farmers an estimated 45-60 €/ha per rotation cycle while maintaining yield. That said, the green manure does occupy the field for 55 days in spring, which may conflict with early rice establishment in some rotations.

Soil organic carbon accumulation of 0.26 percentage points over two years is rapid but not unprecedented for high-biomass legume incorporation on silt loam soils [8]. Whether this gain persists beyond the experimental period depends on continued organic inputs and tillage intensity [9].

Conclusion

Incorporation of *Sesbania aculeata* green manure during the rice phase raised subsequent wheat grain yield by up to 38.2% and post-harvest Olsen-P by 65.8% relative to fallow controls at the same P fertiliser rate. The combination of *S. aculeata* + 60 kg P₂O₅/ha matched the yield of 90 kg P₂O₅/ha alone, pointing to a potential saving of 30 kg P₂O₅/ha per rotation. Soil organic carbon also increased with green manure incorporation. These results support the reintroduction of legume green manures into rice-wheat rotations in temperate Europe as a means to improve P-use efficiency and sustain soil health. Multi-year validation under varying soil types and climatic conditions is warranted before broad adoption.

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