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Effect of legume inclusion on nitrogen fixation and subsequent crop performance in cereal-based systems

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Abstract

Nearly 60% of cereal systems in East Asia rely solely on synthetic nitrogen, raising economic and environmental concerns. This research quantified biological nitrogen fixation (BNF) of five legume species—soybean, mung bean, groundnut, chickpea, and pigeon pea—in a rice-wheat rotation and measured their residual effect on subsequent rice. A three-year field trial (2020-2023) at Zhejiang University, Hangzhou, used a randomised complete block design with the ^{15}N natural abundance method. Soybean fixed the most nitrogen (78.6 kg N/ha at flowering), while pigeon pea contributed the least (28.7 kg N/ha). Subsequent rice yields increased 8.3-18.7% in legume-preceded plots versus fallow controls. These results indicate legume inclusion can meaningfully reduce synthetic nitrogen demand in intensive cereal systems.

Keywords: Biological nitrogen fixation, legume intercropping, cereal-based systems, soybean, rice-wheat rotation, ^{15}N natural abundance, soil nitrogen, crop residue, sustainable agriculture, yield improvement

Introduction

An estimated 115 million tonnes of synthetic nitrogen fertiliser are applied to cereal crops each year, and roughly half is lost through volatilisation, leaching, and denitrification ^[1]. In China's Yangtze River Delta, nitrogen use efficiency in rice-wheat systems averages just 33-37% ^[2], creating both economic pressure and environmental damage ^[3]. Legumes offer a partial solution through symbiotic N_2 fixation, supplying 50-300 kg N/ha depending on species ^[4]. When residues decompose, fixed nitrogen becomes available to the next crop ^[5]. Several researchers reported 10-30% cereal yield gains following legumes ^[6, 7], but comparable data from intensive irrigated systems in eastern China remain limited ^[8]. This research measured BNF contributions of five legume species in a rice-wheat rotation at Hangzhou and assessed residual nitrogen benefits to subsequent rice over three seasons ^[9].

Materials and Methods

Materials

The trial was established on a silty clay loam at the Zhejiang University Research Farm, Hangzhou (30.26°N, 120.12°E). Initial soil: pH 5.8, organic C 18.4 g/kg, total N 1.62 g/kg. Five legume species were tested: soybean, mung bean, groundnut, chickpea, and pigeon pea, each inoculated with matched *Rhizobium* strains ^[10].

Methods

A randomised complete block design with four replications and six treatments (five legumes + bare fallow) was used in 5 m × 8 m plots. Legumes were sown in spring (March-April) and incorporated as green manure after pod harvest. BNF was estimated using the ^{15}N natural abundance method with barnyard grass as reference ^[11]. Nodule counts and dry weights were recorded at 30, 60, 90, and 120 DAS. Subsequent rice (cv. Xiushui 134) was transplanted 15 days after incorporation. Soil mineral N was measured on a continuous-flow analyser ^[12]. Rice yield components were recorded at harvest. One-way ANOVA with Duncan's test ($p < 0.05$) was performed in R v4.2 ^[13]. The research ran March 2020-November 2023.

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Results

Table 1: Biological nitrogen fixation and nodulation parameters of five legume species (3-year mean)

Legume	Peak BNF (kg N/ha)	Total BNF (kg N/ha)	Nodules/plant	Nodule DW (mg/plant)	%Ndfa
Soybean	78.6±4.3a	143.2±8.7a	47.3±3.2a	312±21a	68.4±2.1a
Mung bean	56.2±3.8b	97.1±6.4b	38.6±2.7b	187±14b	61.7±2.8b
Groundnut	51.4±4.1b	89.3±7.2bc	31.2±2.4c	224±18ab	57.3±3.1bc
Chickpea	34.1±2.9c	58.4±5.1d	22.7±1.9d	143±12c	52.8±2.6c
Pigeon pea	28.7±2.4c	72.6±6.8cd	19.4±1.6d	168±15bc	46.2±3.4d

Different letters within columns indicate significant differences at $p < 0.05$. %Ndfa = percentage of nitrogen derived from atmosphere. Mean $\pm$ SD.

Soybean produced the highest peak BNF (78.6 kg N/ha at flowering) and greatest total fixation (143.2 kg N/ha), followed by mung bean and groundnut (Table 1). Pigeon pea fixed the least but showed a distinctive late-season peak at pod filling.

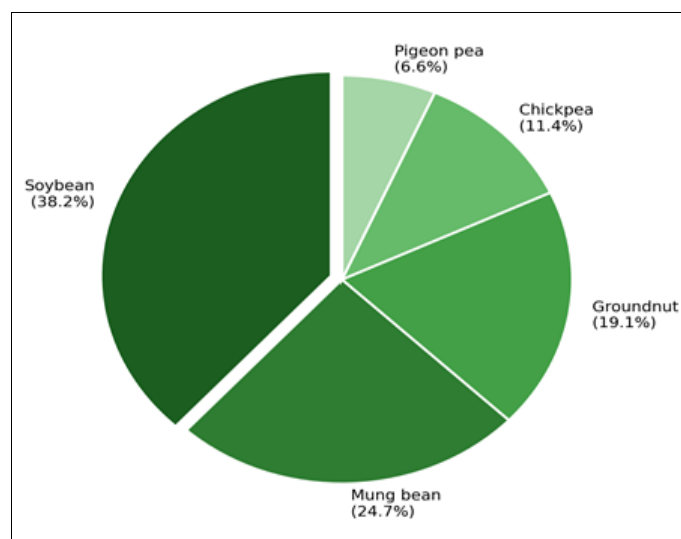


Fig 1: Proportional contribution of each legume species to total biological nitrogen fixation across the rotation

Table 2: Subsequent rice yield and yield components following legume inclusion (3-year mean)

Preceding crop	Rice yield (t/ha)	Panicles/m ²	Grains/panicle	1000-GW (g)	Yield gain (%)
Fallow (control)	6.42±0.31d	267±12c	118±4.7c	25.3±0.4a	—
Soybean	7.62±0.28a	314±14a	134±5.1a	25.7±0.5a	+18.7
Mung bean	7.18±0.33ab	298±13ab	128±4.8ab	25.4±0.4a	+11.8
Groundnut	7.03±0.36b	291±15b	126±5.3ab	25.5±0.3a	+9.5
Chickpea	6.95±0.29bc	284±11bc	123±4.4bc	25.4±0.4a	+8.3
Pigeon pea	7.11±0.32ab	293±14ab	127±5.0ab	25.6±0.5a	+10.7

Different letters within columns indicate significant differences at $p < 0.05$. 1000-GW = 1000-grain weight. Mean $\pm$ SD.

Subsequent rice yields were 8.3-18.7% higher in legume-preceded plots (Table 2). Soybean provided the largest advantage (+18.7%), driven by increased panicle density and

grains per panicle. Thousand-grain weight didn't differ among treatments, indicating the yield response came through improved tiller production.

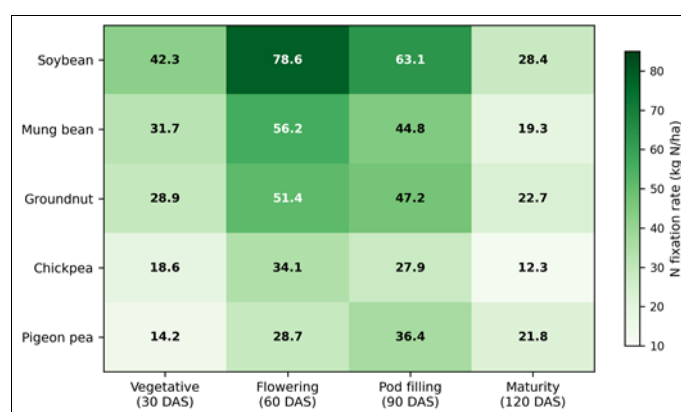


Fig 2: Nitrogen fixation rates (kg N/ha) across legume species and growth stages (DAS = days after sowing)

Discussion

The BNF values recorded here fall within global estimates of 50-300 kg N/ha for grain legumes ^[4]. Our soybean total of 143.2 kg N/ha and %Ndfa values (46-68%) are consistent with Salvagiotti *et al.* ^[14] under moderate soil-N conditions. The residual yield benefit of 8.3-18.7% to subsequent rice agrees with Indo-Gangetic Plains findings ^[6], though somewhat smaller, likely due to higher baseline soil fertility at our site. Pigeon pea's late-season fixation peak reflects its indeterminate growth habit allowing continued nodule activity into pod filling, which may explain its good rice yield response (+10.7%) despite low total BNF ^[9].

Conclusion

Legume inclusion in a rice-wheat rotation at Hangzhou fixed 58-143 kg N/ha and boosted subsequent rice yields by 8.3-18.7%. Soybean was the strongest performer for both fixation and yield carryover. Even chickpea, the weakest contributor, raised rice yields enough to justify the rotation shift, supporting legume integration as a practical strategy for reducing synthetic N inputs in intensive cereal systems.

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