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Crop Proportion and Fertility Management Influence Canopy Development and Productivity of Pearl Millet-Green Gram Intercropping

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

A field experiment was conducted to evaluate the effects of pearl millet-green gram intercropping proportion and graded fertility levels on crop growth, physiological traits and productivity of the component crops. The experiment was laid out in a split-plot design with three replications and comprised four intercropping treatments in the main plots, viz., sole pearl millet, sole green gram, pearl millet + green gram in 2:1 and 2:2 row proportions, and five fertility levels in the subplots (control, 50% recommended dose of fertiliser (RDF), 75% RDF, 100% RDF and 125% RDF). Growth and yield data collected according to standard procedures were

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subjected to analysis of variance. The results revealed that intercropping significantly influenced pearl millet plant population, leaf area index (LAI), chlorophyll content, tillers plant^{-1} and grain yield. Pearl millet grain yield was highest under sole cropping (1997 kg ha^{-1}) and declined to 1809 and 1551 kg ha^{-1} under 2:1 and 2:2 intercropping, respectively. Green gram grain yield was 953 kg ha^{-1} under sole cropping and 308 and 455 kg ha^{-1} under 2:1 and 2:2 intercropping, respectively. In contrast, increasing fertility progressively enhanced canopy development, chlorophyll content and yield attributes of both crops. Pearl millet grain yield increased from 1440 kg ha^{-1} under the control to 2020 kg ha^{-1} under 125% RDF, while green gram yield increased from 466 to 632 kg ha^{-1}. However, grain yield at 100% RDF (1955 kg ha^{-1} in pearl millet and 620 kg ha^{-1} in green gram) was statistically comparable with that at 125% RDF. The competition ratio indicated greater competitive ability of pearl millet than green gram, although increasing the green gram proportion from 2:1 to 2:2 improved its competitive position. Overall, crop proportion regulated the competitive balance and component-crop productivity, whereas fertility primarily improved crop growth and yield formation.

Keywords: Pearl millet; green gram; intercropping; crop proportion; fertility management; leaf area index; chlorophyll content; grain yield; competition ratio; recommended dose of fertiliser.

1. Introduction

Pearl millet (*Pennisetum glaucum* L.) is an important cereal for resource-constrained production environments, where efficient utilisation of available land and nutrients is essential for sustaining productivity. Intercropping pearl millet with a short-duration legume such as green gram (*Vigna radiata* L.) offers an opportunity to combine cereal and legume production within the same land area (Kumar *et al.,* 2024). However, the performance of such systems is strongly influenced by the proportion of the component crops (Rani *et al.,* 2017). Changes in crop proportion alter plant population, canopy structure and the competitive environment, ultimately affecting the growth and yield contribution of each crop. Fertility is another important determinant of intercrop performance. Nutrient availability influences leaf development, chlorophyll formation, tillering, branching and reproductive growth (Karthika *et al.,* 2018). In a cereal-legume association, however, the response to fertiliser may differ from that of sole crops because the component crops simultaneously interact for available resources. Hence, matching crop proportion appropriately with fertility level is important for achieving productive coexistence of pearl millet and green gram (Shilpa *et al.,* 2025). A recent pearl millet-pulse field study likewise demonstrated that intercropping system and nutrient-management practices jointly affect pearl millet growth and yield, underscoring the need to evaluate crop arrangement and fertility together (Shiyal et al., 2023). Similarly, field evaluation of pearl millet-mung bean systems showed that nitrogen rate and row arrangement significantly influenced several pearl millet yield-related traits, indicating the importance of considering both factors simultaneously (Lakew, 2026).

The productivity of an intercrop is determined not only by final grain yield but also by how the component crops establish and develop their canopies during the growing season. Plant population, leaf area index (LAI) and chlorophyll content provide useful indicators of crop establishment, canopy development and physiological status, respectively (Singh *et al.,* 2024). Changes in these traits can help explain subsequent differences in yield attributes and grain production. In pearl millet-green gram intercropping, increasing the proportion of green gram may increase its contribution to the system but can simultaneously intensify competition with pearl millet. Similarly, increasing fertility may improve crop growth and alter the competitive balance between the two crops. Evaluating these responses across graded fertility levels is therefore necessary to identify a suitable combination of crop proportion and nutrient supply (Yadav *et al.,* 2023). At a broader scale, a global meta-analysis showed that nitrogen-input strategy can modify land-use advantage and fertiliser-nitrogen efficiency in intercropping systems, supporting explicit assessment of fertility management within cereal-legume associations (Liu et al., 2024). Integrated nutrient-management treatments have also been reported to alter N, P and K content and uptake in green gram, emphasising the crop's responsiveness to nutrient-management strategy (Kamal et al., 2026).

From a practical perspective, successful pearl millet-green gram intercropping requires balancing the population of the two component crops with the nutrient supply available to the system. Selection of an appropriate intercrop proportion is particularly important where farmers seek to obtain both cereal and pulse output from the same land area, while fertility management determines whether the component crops can adequately develop their productive potential. Previous studies on cereal-legume intercropping have largely focused on component yield, system productivity and economic returns (Ram & Meena, 2014; G *et al.,* 2025). Comparatively little attention has been given to linking crop proportion and fertility gradients with crop-specific canopy development and physiological responses and subsequently relating these changes to yield formation. In particular, the extent to which increasing fertility modifies the growth and productivity responses of pearl millet and green gram under different crop proportions remains insufficiently resolved. A combined assessment of plant population, LAI, chlorophyll content, yield attributes and grain yield can provide a better understanding of these crop interactions.

The present study was conducted to evaluate the effects of pearl millet-green gram intercropping proportion and graded fertility levels on crop establishment, canopy development, chlorophyll content, yield attributes and grain yield of the component crops.

2. Materials and Methods

The experiment was conducted during the *kharif* seasons of 2024 and 2025 at the Research Farm, Rajasthan Agricultural Research Institute, Durgapura, Jaipur. Geographically, the site is situated at 7547 East longitude and 2651 North latitude, at an altitude of 390 m above mean sea level in Jaipur district, Rajasthan. The region falls within the Semi-Arid Eastern Plains Zone (IIIa) of Rajasthan. The mean maximum and minimum temperatures and relative humidity during the experimental period ranged from 30.0 to 36.5°C, 21.5 to 26.1°C, 71.6 to 93.6%, and 58.4 to 81.7%, respectively. The average rainfall and wind speed during the experiment were 77 mm and 5.2 kmph, respectively. Initial soil analysis of the experimental site revealed 157.69 kg ha^{-1} available nitrogen, 35.55 kg ha^{-1} available phosphorus, 198.10 kg ha^{-1} available potassium and 0.27% organic carbon. The soil had a loamy sand texture with a pH of 8.00.

The experiment was laid out in a split-plot design with four intercropping treatments in the main plots {I_1: sole pearl millet at 45 cm row spacing, I_2: sole green gram at 30 cm row spacing, I_3: pearl millet + green gram (2:1) at 30 cm row spacing and I_4: pearl millet + green gram (2:2) at 30 cm row spacing} and five fertility treatments in the subplots {F_1: control, F_2: 50% recommended rate of fertiliser (RDF), F_3: 75% RDF, F_4: 100% RDF and F_5: 125% RDF}, with three replications. The experiment had a total of 60 plots, with each plot measuring 5.0 m × 3.60 m. Pearl millet variety RHB-233 and green gram variety RMG-975 were sown at rates of 4 and 16 kg ha^{-1}, respectively. The prescribed row arrangement and spacing for each treatment were maintained uniformly in all intercropping plots to ensure the desired plant population and crop geometry. The recommended dose of fertiliser for pearl millet was 60 kg N, 30 kg P_2O_5 and 20 kg K_2O ha^{-1}. Nitrogen, phosphorus and potassium were supplied through urea (46% N), single super phosphate (SSP, 16% P_2O_5) and muriate of potash (MOP, 60% K_2O), respectively.

Growth parameters were measured at 30 days after sowing (DAS) and at harvest in pearl millet, whereas observations for green gram were taken at 25 DAS and at harvest. Five plants from each plot were tagged, data were collected from these plants, and the mean was calculated. All parameters were recorded following standard agronomic procedures, and the data were subjected to analysis of variance (ANOVA) according to Gomez and Gomez (1984).

3. Results and Discussion

3.1 Crop Establishment and Canopy Development

Intercropping ratio significantly influenced pearl millet plant population at both 30 DAS and harvest (Table 1). Sole pearl millet recorded the highest population (11.77 and 10.30 plants m^{-1} row length, respectively), whereas the population under pearl millet + green gram was lower, ranging from 6.70-6.92 plants m^{-1} at 30 DAS and 6.19-6.24 plants m^{-1} at harvest. The difference between the 2:1 and 2:2 ratios was not significant. In contrast, green gram population did not differ significantly among the intercropping treatments at either 25 DAS or harvest. The lower pearl millet population under intercropping primarily reflects the altered spatial allocation of rows to the two component crops rather than a difference in establishment within the allocated rows. The similar pearl millet populations under 2:1 and 2:2 also indicate that the subsequent reduction in pearl millet productivity between these ratios was not associated with a substantial difference in final pearl millet population. Thus, differences in crop performance between the two intercropping ratios are more appropriately interpreted in relation to the competitive environment created by the component-crop proportions. Similar findings have been reported by Sharma *et al.* (2009).

Table 1. Effect of intercropping ratio and fertility level on the establishment and growth attributes of pearl millet and green gram

Treatments	Plant population (m^{-1} row length)				Leaf area index				Chlorophyll content (mg g^{-1} fresh leaves)	
	Pearl millet		Green gram		Pearl millet		Green gram			
	30 DAS	Harvest	25 DAS	Harvest	30 DAS	60 DAS	25 DAS	Harvest	Pearl millet	Green gram
Intercropping ratio										
Sole pearl millet	11.77	10.30	-	-	2.84	4.57	-	-	3.70	-
Sole green gram	-	-	12.31	11.54	-	-	0.81	2.89	-	3.22
Pearl millet + Green gram (2:1)	6.92	6.19	11.82	10.62	2.55	4.01	0.72	2.58	3.36	2.93
Pearl millet + Green gram (2:2)	6.70	6.24	11.67	10.94	2.52	4.03	0.71	2.55	3.26	2.84
SEm±	0.18	0.16	0.27	0.24	0.04	0.07	0.01	0.05	0.04	0.05
CD (*P*=0.05)	0.59	0.54	NS	NS	0.14	0.24	0.04	0.16	0.13	0.16
CV (%)	11.68	11.86	12.30	11.79	8.80	9.67	9.01	9.80	6.56	8.85
Fertility levels										
Control	8.40	7.53	11.85	10.66	2.22	3.49	0.65	2.26	2.87	2.56
50% RDF	8.56	7.73	12.14	11.06	2.49	3.97	0.73	2.57	3.27	2.90
75% RDF	8.59	7.85	11.97	11.19	2.69	4.30	0.77	2.77	3.52	3.10
100% RDF	8.27	7.38	11.71	10.69	2.88	4.57	0.79	2.86	3.70	3.18
125% RDF	8.50	7.39	12.00	11.57	2.92	4.70	0.81	2.90	3.83	3.25
SEm±	0.23	0.19	0.30	0.27	0.05	0.08	0.01	0.05	0.05	0.05
CD (P=0.05)	NS	NS	NS	NS	0.13	0.24	0.04	0.15	0.14	0.16
CV (%)	11.39	10.66	10.82	10.33	7.60	8.50	7.62	8.49	6.26	7.75

Fertility level did not significantly affect the plant population of either pearl millet or green gram at the observed stages. Pearl millet population at harvest ranged from 7.38 to 7.85 plants m^{-1}, while green gram population ranged from 10.66 to 11.57 plants m^{-1}. This indicates that the major fertility response occurred after crop establishment rather than through changes in stand density.

In contrast, fertility markedly influenced canopy development (Table 1). Pearl millet LAI increased from 2.22 at 30 DAS under the control to 2.92 under 125% RDF, while LAI at 60 DAS increased from 3.49 to 4.70. Green gram LAI similarly increased from 0.65

to 0.81 at 25 DAS and from 2.26 to 2.90 at harvest. The differences among fertility levels were significant for both crops. The increase in LAI with increasing fertility indicates greater leaf expansion and canopy development under improved nutrient availability (Kumar *et al.,* 2018). The response was particularly evident in pearl millet at 60 DAS, suggesting that nutrient supply supported greater canopy maintenance during the active crop growth period. However, the increase from 100 to 125% RDF was relatively small compared with the response from the lower fertility levels, indicating a tendency towards saturation at higher fertiliser supply (Azizah *et al.,* 2025). Intercropping reduced LAI of both component crops compared with their respective sole crops. Pearl millet LAI at 30 and 60 DAS was 2.84 and 4.57 under sole cropping, compared with 2.55 and 2.52, and 4.01 and 4.03, respectively, under the two intercrop ratios. Green gram LAI at 25 DAS and harvest was 0.81 and 2.89 under sole cropping, compared with 0.71 and 0.72, and 2.55 and 2.58, respectively, under intercropping. The lower component-wise LAI in the intercrop suggests that the shared growing environment restricted the canopy development of individual crops relative to their sole stands (Mohamed *et al.,* 2020).

3.2 Chlorophyll Content

Chlorophyll content was significantly affected by both intercropping ratio and fertility level (Table 1). Under intercropping, pearl millet chlorophyll content was 3.36 and 3.26 mg g^{-1} fresh leaves under the 2:1 and 2:2 ratios, respectively, compared with 3.70 mg g^{-1} in sole pearl millet. Green gram chlorophyll content was 2.93 and 2.84 mg g^{-1} under 2:1 and 2:2, respectively, compared with 3.22 mg g^{-1} in sole green gram. The lower chlorophyll concentration in the intercrop indicates that the component crops experienced a different growth environment from their respective sole stands. The relatively small difference between 2:1 and 2:2, particularly in pearl millet, suggests that increasing the green gram proportion did not substantially modify leaf chlorophyll beyond the effect associated with intercropping itself.

Increasing fertility increased chlorophyll content in both crops. Pearl millet chlorophyll content increased from 2.87 mg g^{-1} under the control to 3.83 mg g^{-1} under 125% RDF, while green gram chlorophyll content increased from 2.56 to 3.25 mg g^{-1}. The significant response to fertility is consistent with the concurrent increase in LAI and indicates improved physiological status of the foliage with greater nutrient availability. Nevertheless, the difference between 100 and 125% RDF was relatively small and fell within the reported critical difference, indicating that the additional fertiliser beyond the recommended level did not provide a statistically significant improvement in chlorophyll concentration. Similar increases in chlorophyll content with increasing fertility levels have also been reported by Khatun and Mollah (2023) and Hosseini *et al.* (2023).

3.3 Yield Attributes and Grain Yield of Pearl Millet

Intercropping ratio significantly affected total tillers $plant^{-1}$ and grain yield of pearl millet, whereas days to ear-head emergence and ear-head girth were not significantly influenced (Table 2). Sole pearl millet produced 4.24 tillers $plant^{-1}$ and 1997 kg ha^{-1} grain yield. These values declined to 3.88 tillers $plant^{-1}$ and 1809 kg ha^{-1} under the 2:1 ratio and further to 3.82 tillers plant-1 and 1551 kg ha^{-1} under the 2:2 ratio. The progressive reduction in pearl millet grain yield with increasing green gram proportion indicates increasing competition imposed by the associated legume. The reduction was approximately 9.4% under 2:1 and 22.3% under 2:2 compared with sole pearl millet. Importantly, the two intercrop ratios had similar pearl millet plant populations at harvest, whereas grain yield differed considerably. This suggests that the yield reduction under 2:2 was not simply a consequence of a lower pearl millet stand but was associated with the altered crop proportion and competitive environment during crop growth. These findings are in accordance with the work of Nelson *et al.* (2022), Sahoo *et al.* (2023) and Sharmili *et al.* (2021).

Table 2. Effect of intercropping ratio and fertility level on the yield and yield attributes of pearl millet

Treatments	Days to ear head emergence	Total tillers $plant^{-1}$	Ear head girth (cm)	Grain yield (kg ha^{-1})
Intercropping ratio				
Sole pearl millet	47.37	4.24	33.87	1997
Sole green gram	-	-	-	-
Pearl millet + Green gram (2:1)	46.16	3.88	32.83	1809
Pearl millet + Green gram (2:2)	45.71	3.82	32.14	1551
SEm±	0.92	0.05	0.45	25
CD (*P*=0.05)	NS	0.17	NS	81
CV (%)	10.83	7.29	7.41	7.63
Fertility level				
Control	45.89	3.27	27.05	1440
50% RDF	46.04	3.76	31.42	1678
75% RDF	46.65	4.07	33.71	1836
100% RDF	46.70	4.35	35.88	1955
125% RDF	46.79	4.46	36.69	2020
SEm±	1.11	0.07	0.57	32
CD (P=0.05)	NS	0.19	1.82	91
CV (%)	10.10	7.15	7.85	7.62

Fertility level significantly affected tillering, ear-head girth and grain yield, but not days to ear-head emergence. Pearl millet grain yield increased from 1440 kg ha^{-1} under the control to 1678, 1836, 1955 and 2020 kg ha^{-1} with 50, 75, 100 and 125% RDF, respectively. Total tillers increased from 3.27 to 4.46 $plant^{-1}$, while ear-head girth increased from

27.05 to 36.69 cm across the same fertility gradient. The yield response therefore closely followed improvements in the yield-forming traits, particularly tillering and ear-head development. However, although 125% RDF produced the numerically highest grain yield, it was statistically comparable with 100% RDF. Thus, increasing fertility improved pearl millet productivity substantially up to the recommended fertiliser level, while a further increase to 125% RDF did not result in a statistically significant yield advantage. These findings are supported by the work of Qadir *et al.* (2021) and Prakash *et al.* (2026).

3.4 Yield Attributes and Grain Yield of Green Gram

Green gram responded differently to changes in intercropping ratio (Table 3). Sole green gram produced 7.04 branches plant^{-1} and 953 kg ha^{-1} grain yield. Under 2:1 and 2:2 intercropping, the number of branches decreased significantly to 6.37 and 6.21 plant^{-1}, respectively. Seeds pod^{-1} and test weight were not significantly affected, while grain yield was significantly reduced to 308 and 455 kg ha^{-1} under 2:1 and 2:2, respectively. The reduction in green gram yield was considerably greater than that observed for pearl millet. Relative to sole green gram, grain yield declined by approximately 67.7% under 2:1 and 52.3% under 2:2. Interestingly, increasing the green gram proportion from 2:1 to 2:2 increased green gram grain yield by about 48%, despite the absence of a significant difference in seeds pod^{-1} and test weight. This indicates that the greater representation of green gram in the 2:2 arrangement improved its overall yield contribution primarily through its greater proportion within the intercrop rather than through a marked improvement in individual reproductive traits. Similar findings have been reported by Chaudhary *et al.* (2018) and Kumar *et al.* (2023).

Table 3. Effect of intercropping ratio and fertility level on the yield and yield attributes of green gram

Treatments	Branches plant^{-1}	Seeds pod^{-1}	Test weight (g)	Grain yield (kg ha^{-1})
Intercropping ratio				
Sole pearl millet	-	-	-	-
Sole green gram	7.04	10.17	39.68	953
Pearl millet + Green gram (2:1)	6.37	9.78	39.23	308
Pearl millet + Green gram (2:2)	6.21	9.63	38.19	455
SEm±	0.11	0.14	0.50	9
CD (P=0.05)	0.35	NS	NS	29
CV (%)	8.98	7.50	7.00	8.51
Fertility levels				
Control	5.43	8.10	33.37	466
50% RDF	6.31	9.49	37.87	538
75% RDF	6.81	10.30	40.42	603
100% RDF	7.02	10.64	41.46	620
125% RDF	7.13	10.78	42.05	632
SEm±	0.12	0.17	0.60	11
CD (P=0.05)	0.35	0.49	1.72	31
CV (%)	8.04	7.40	6.57	8.02

Fertility level significantly improved all measured yield attributes and grain yield of green gram. Grain yield increased progressively from 466 kg ha^{-1} under the control to 538, 603, 620 and 632 kg ha^{-1} under 50, 75, 100 and 125% RDF, respectively. Branches plant^{-1} increased from 5.43 to 7.13, seeds pod^{-1} from 8.10 to 10.78 and test weight from 33.37 to 42.05 g. These responses demonstrate that improved fertility enhanced both vegetative and reproductive development of green gram. Nevertheless, as observed in pearl millet, the increase in grain yield from 100 to 125% RDF was small (620 to 632 kg ha^{-1}) relative to the critical difference of 31 kg ha^{-1}. Hence, the 125% RDF treatment did not provide a statistically significant grain-yield advantage over 100% RDF. Similar findings have been reported by Pareek *et al.* (2022) and Chandel *et al.* (2018).

3.5 Competition Ratio

Competition ratio showed clear competitive dominance of pearl millet over green gram in both intercropping ratios (Fig. 1). Pearl millet recorded CR values of 1.40 and 1.62 under 2:1 and 2:2 ratios, respectively, whereas green gram recorded 0.45 and 0.83. Thus, increasing the green gram proportion from 2:1 to 2:2 improved its competitive ability, although pearl millet remained the dominant competitor. Fertility levels caused only minor variation in CR, with pearl millet remaining around 0.74-0.76 and green gram around 0.31-0.32. This indicates that increasing fertility did not substantially alter the relative competitive relationship between the component crops, despite improving their growth and yield.

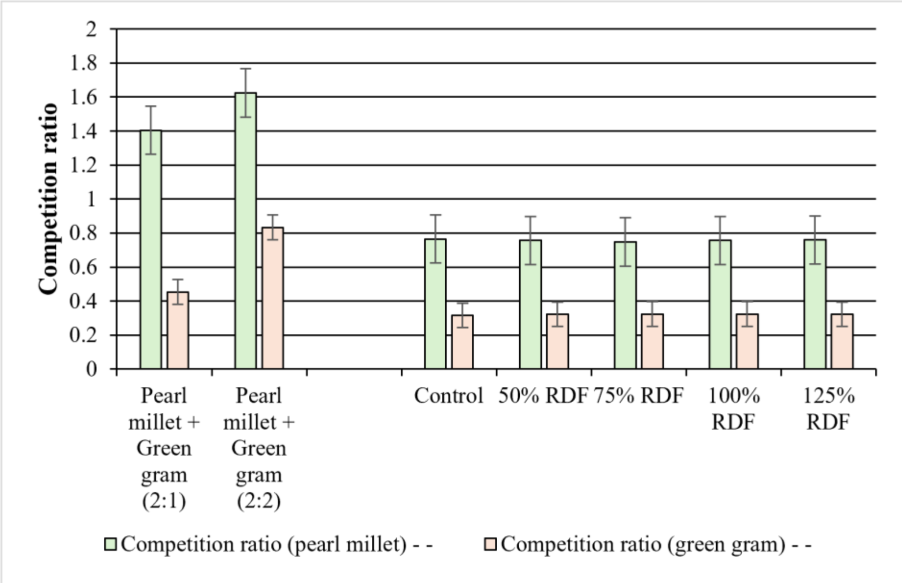

Fig. 1. Effect of intercropping ratio and fertility level on competition ratio

4. Conclusion

Crop proportion and fertility management jointly influenced canopy development, physiological performance and productivity in the pearl millet-green gram intercropping system. Sole pearl millet and sole green gram produced the highest grain yields of their respective crops, while intercropping reduced component-crop yield because of altered population distribution and competition. Increasing the green gram proportion from 2:1 to 2:2 reduced pearl millet yield but increased the grain-yield contribution and competitive position of green gram. Fertility improved leaf area index, chlorophyll content, tillering or branching, yield attributes and grain yield in both crops. Grain yield increased progressively with fertility, but 100% RDF produced yields statistically comparable with 125% RDF for both pearl millet and green gram, indicating limited additional yield benefit from fertiliser beyond the recommended level under the conditions evaluated. Pearl millet remained the dominant competitor across intercropping proportions. These results indicate that crop proportion should be selected together with an appropriate fertility level to balance the productivity of the component crops while maintaining the competitive stability of the intercropping system.

5. Limitation

The findings are specific to the two *kharif* seasons, the experimental site at Durgapura, Jaipur, the pearl millet and green gram varieties used, the two intercropping proportions evaluated, and the tested fertility range. Consequently, the observed canopy, yield and competition responses should be interpreted within these experimental conditions. Validation across additional locations, seasons, soil types, cultivars and crop proportions would help determine the consistency and broader applicability of the identified crop proportion–fertility responses.

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Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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