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Research Article

Keywords: Intercropping, Resource complementarity, Nutrient uptake, Drip irrigation, Arid systems

Posted Date: August 7th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10449390/v1

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Additional Declarations: No competing interests reported.

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Acknowledgments

The authors gratefully acknowledge the support provided by colleagues at the Institute of Soil Fertilizer and Water Saving Agriculture, Gansu Academy of Agricultural Sciences (GAAS), China, for their assistance in managing the field experiments and collecting experimental data over the study period. The authors are especially thankful to colleagues at the National Research Center of Intercropping (NRCI), The Islamia University of Bahawalpur, Pakistan for their support with data analysis and figure preparation.

Funding

This study was financially supported by the Gansu Province's funding for High-End Foreign Experts Introduction Program (Research on Key Technologies for Diversified Grain-Legume Planting with Mulch Drip Irrigation); International Outstanding Young Scholars Program (Research on Efficient Resource Utilization in Maize-Legume Intercropping Systems).

Abstract

Intensive sole cropping, particularly under conventional flood irrigation, often results in low resource use efficiency and reduced system productivity in arid regions. This study investigated the interactive effects of irrigation methods and cropping systems on nutrient dynamics and resource use in a soybean-maize intercropping system (SMi). A three-year field experiment (2023-2025) was conducted in an arid agroecosystem to evaluate three irrigation methods (flood irrigation, FI; drip irrigation without mulch, DI; and drip irrigation with plastic mulch, DIm) applied to sole maize, sole soybean, and SMi. We measured crop growth, nitrogen (N) and phosphorus (P) uptake, system productivity, and resource use efficiencies. Compared to FI and DI, DIm consistently increased leaf area, dry matter, and nitrogen and phosphorus uptake across all cropping systems. Under SMi-DIm, intercropped soybean and maize attained 72% and 75% of their corresponding sole-crop yields, substantially reducing the intercropping yield gap compared to conventional FI. Similarly, SMi-DIm exhibited clear system-level advantages, with land equivalent ratio (LER) for land (LER_L: 1.47), nitrogen (LER_N: 1.56), and phosphorus (LER_P: 1.61), and water equivalent ratio (WER: 1.43), all exceeding one. These improvements translated into the highest net returns (3077 USD ha^{-1}), which were 95% and 10% higher than sole soybean and sole maize, respectively. Overall, this study demonstrates that the synergy between drip irrigation with plastic mulch and legume-cereal intercropping enhances resource complementarity and nutrient (N and P) uptake, offering a viable climate-resilient pathway for sustainable agricultural intensification in water-scarce regions without requiring proportional increases in resource inputs.

Keywords:

Intercropping; Resource complementarity; Nutrient uptake; Drip irrigation; Arid systems.

1. Introduction

Irrigated areas typically have arid to semi-arid conditions and are known for higher crop yields with intensive resource application, particularly water and nutrients (Shi et al., 2025). Increasing crop production in these regions, mainly for cereals and legumes, is crucial for maintaining national and global food security, as more than 40% of world food crops come from irrigated fields (Mehta et al., 2024; Zhang et al., 2022). However, poor soil quality and fertility, water scarcity, and climate change are the primary factors limiting further increase in crop production in these areas (Li et al., 2023). Given these challenges, crop yield formation largely depends on genetics, agronomic management, growing conditions, and their interactions; among these, water application methods—such as flood irrigation, drip irrigation, or drip irrigation with plastic mulch—and their impact on nutrient use efficiency are key crop management measures (Li et al., 2023; Zhang et al., 2022). Currently, farmers are applying water and synthetic fertilizers, primarily nitrogen (N) and phosphorus (P), at rates higher than what the crops actually require (Raza, Din, Gul, et al., 2024); although this approach is helping them to achieve high crop yields, but these immoderate water and nutrient application strategies are not only decreasing water and nutrient use efficiencies but also leading to resource wastage and environmental pollution (Li et al., 2023; Zhang et al., 2022). Therefore, optimizing or developing resource-efficient and environmentally friendly cropping systems, e.g., intercropping (Dong et al., 2018; Duchene et al., 2017), and agronomic management practices, e.g., irrigation systems for water and nutrient application, which can increase crop yields while conserving valuable resources and improving efficiency, are essential for future sustainable agricultural intensification (Raza, Din, Shah, et al., 2024; Yin et al., 2024).

Irrigation water and its application method strongly regulate crop growth and yield (Yaghi et al., 2013). Adequate water supply at critical growth stages optimizes physiological processes and enhances nutrient uptake (Ullah et al., 2019). Conversely, water shortage or inefficient application reduces both yield and water use efficiency (Li et al., 2009). With climate change projected to exacerbate water scarcity globally (IPCC, 2014), optimizing irrigation is urgent. Flood irrigation remains dominant in developing countries but is highly inefficient due to distribution losses, evaporation, and deep percolation (Ullah et al., 2019; Yaghi et al., 2013). In contrast, drip irrigation with or without plastic mulch depending on the crop type, area, and growing season, is a modern and efficient method increasingly adopted in arid-irrigated areas to conserve water and enhance yield (Li et al., 2023; Wang et al., 2011). However, the literature on plastic mulch presents conflicting results. Some studies report that drip irrigation with plastic mulch improves soil moisture and temperature, boosts germination and root growth, and shortens the crop cycle, thereby increasing yield (Gerçek et al., 2009; Li et al., 2022; Meng et al., 2020; Wang et al., 2024; Zhou et al., 2021). Others warn that prolonged use of plastic mulch can cause residual pollution, degrade soil structure and microbial diversity, alter soil chemistry, and ultimately reduce yield and net economic returns (Jiang et al., 2017; Tang, 2023; Wang et al., 2011; Zhang et al., 2023). Importantly, most previous research has focused on sole cropping systems (Li et al., 2009; Ullah et al., 2019; Wang et al., 2024; Zhang et al., 2022), with limited attention to how drip irrigation and plastic mulch affect intercropping systems-despite growing interest in intercropping as a sustainable practice (Feng et al., 2020; Li et al., 2020).

Intercropping, especially legume-cereal mixtures, is designed on ecological principles to enhance resource productivity and reduce anthropogenic inputs (Ahmed et al., 2018; Feng et al., 2019). Legume-based intercropping combinations can (a) support sustainable intensification (Fan et al., 2020; Yu et al., 2015), (b) improve resource use efficiency (Brooker et al., 2015; Willey, 1990), and (c) enhance soil fertility (Brooker et al., 2015; Xia et al., 2013). Overyielding under mixed or strip intercropping arises when component species exploit resources complementarily in space or time, or when facilitative interactions between species enhance resource use and crop performance (Ahmed et al., 2018; Dong et al., 2018; Duchene et al., 2017). Such interactions promote niche differentiation and reduce interspecific competition, resulting in higher system productivity than in sole cropping (Iqbal et al., 2018; Willey, 1990; Yu et al., 2015), particularly when legumes are combined with cereals such as maize or wheat (Feng et al., 2019; Raza, Din, Shah, et al., 2024). However, the magnitude of these interactions largely depends on crop architecture, growth duration, root systems, and agronomic practices (Ahmed et al., 2018; Brooker et al., 2015; Duchene et al., 2017). Therefore, selecting appropriate crop combinations (cereals with legumes) that differ in resource utilization across time and space and management practices (irrigation and fertilization methods) that promote facilitation over competitive interactions is crucial under climate change and resource limitation (Rosa-Schleich et al., 2019; Shi et al., 2025; Wezel et al., 2014).

Maize (*Zea mays*) is the second most important food crop globally, grown on ~197 million hectares (ha), mostly in sole cropping system with high inputs (Erenstein et al., 2022). Similarly, soybean (*Glycine max*) is the leading legume for food, feed, and oil, covering >122 million ha (Terzić et al., 2018). Expansion of both crops is limited by land, water, and nutrient constraints (Feng et al., 2020; Iqbal et al., 2018). Yet the world must increase crop production, especially of cereals and legumes, by 60–70% to feed 9 billion people by 2050 (Binns et al., 2021). Thus, we propose that soybean/maize intercropping (SMi) using drip irrigation with plastic mulch (Fig. 1) can provide a sustainable and resource-efficient alternative to the current resource-intensive sole maize cropping system, maintaining or enhancing production of both crops with less land, water, and fertilizer. Thus, this experiment was conducted to determine how different irrigation methods (flood verses drip with or without plastic mulch) affect crop growth, resource use, and farm profitability of soybean and maize under intercropping and sole cropping systems. Here, we hypothesized that SMi under drip irrigation with plastic mulch will (i) achieve higher system-level resource use advantages, quantified by land equivalent ratios (LER) for P (LER_P), N (LER_N), and land (LER_L), and water equivalent ratio (WER) compared to sole soybean or maize cropping systems, (ii) produce additional soybean yield without significantly reducing maize yield (the primary food/feed crop for farmers in arid-irrigated conditions), thereby enhancing economic sustainability. Overall, these results will provide both practical and theoretical insights for farmers and policymakers promoting the adoption of maize-based legume intercropping systems to attain stable and higher crop yields and economic profits while reducing environmental impacts, not only in arid-irrigated areas but also in other maize- and soybean-producing regions.

Insert Figure 1; Here

2. Materials and methods

2.1 Research location

This study was conducted during the maize growing seasons from April to October in 2023, 2024, and 2025 at the research farm of the Gansu Academy of Agricultural Sciences, located in Zhangye (38°85′ N, 100°81′ E; 1555 m), Gansu Province, Northwest China. Prior to sowing in April 2023, the experimental soil was classified as sandy loam and exhibited a pH of 8.5, organic matter content of 12.5 g kg^{-1}, total N concentration of 0.8 g kg^{-1}, available P concentration of 13.7 mg kg^{-1}, available K concentration of 223.6 mg kg^{-1}, and a bulk density of 1.4 Mg m^{-3}. In the study area, maize and wheat are largely grown as sole crops under input-intensive production systems, whereas grain legumes are cultivated only on a limited scale, typically along field margins for household consumption. The research site has a continental climate with an average annual temperature of 7.7 °C, a frost-free period of 112-145 days, and annual rainfall <150 mm, with most occurring during the monsoon season (Fig. 2).

Insert Figure 2; Here

2.2 Experimental details

The field experiment was established using a split-plot design with three replicates. The experimental treatments consist of three cropping systems (main plots, sole soybean; SS, sole maize; SM, and soybean/maize intercropping; SMi) and three irrigation methods (sub-plots, flood irrigation; FI, drip irrigation without plastic mulch; DI, and drip irrigation with plastic mulch; DIm). Each block had an area of 576 m^2 (72 m × 8 m), each main plot measured 192 m^2 (24 m × 8 m), and each sub-plot measured 64 m^2 (8 m × 8 m). A 1-m buffer distance was maintained between main plots, sub-plots, and blocks. In all treatments, we adopted the locally practiced narrow-wide-row configuration, where two rows of maize or soybean were planted with a 40 cm row spacing, forming one strip of narrow rows, followed by a 60 cm gap as a wide row between strips (Fig. 3). Soybean and maize were planted at 180,000 and 120,000 plants ha^{-1} in SS and SM, respectively. In SMi, each species received 50% of its sole crop density (soybean: 90,000 plants ha^{-1}; maize: 60,000 plants ha^{-1}), which resulted in the total planting density of the intercropping system being equal to that of a sole crop on a per-land-area basis (i.e., the sum of the two intercrop densities equals the density of one sole crop), as each intercrop occupied 50% of the land (Van Der Werf et al., 2021).

Insert Figure 3; Here

Each year, a determinate soybean variety 'Longhuang-2', and a high-yielding maize hybrid 'Xianyu-335', were simultaneously planted across the treatments during the last week of April. Soybean was harvested in the first week of September, and maize in the first week of October each year. Crop growth periods for soybean and maize under sole and intercropping systems are shown in Figure 4. For sole crops, N and P were applied at 375 kg N ha^{-1} and 225 kg P_2O_5 ha^{-1} for maize, and 225 kg N ha^{-1} and 120 kg P_2O_5 ha^{-1} for soybean. For intercropping, each species received

50% of its sole crop rate (maize: 187.5 kg N ha^{-1} and 112.5 kg P_2O_5 ha^{-1}; soybean: 112.5 kg N ha^{-1} and 60 kg P_2O_5 ha^{-1}), consistent with the replacement design. For sole maize, 95 kg N ha^{-1} was applied as basal and the remaining 280 kg N ha^{-1} was applied in seven equal split doses of 40 kg N ha^{-1} each at 10-day intervals after germination. For sole soybean, 85 kg N ha^{-1} was applied as basal and the remaining 140 kg N ha^{-1} in five equal split doses of 28 kg N ha^{-1} each at 10-day intervals after germination. For intercropping, based on the 50% rates, total N was 187.5 + 112.5 = 300 kg N ha^{-1}. Basal N for intercropping was 47.5 kg N ha^{-1} (from maize) + 42.5 kg N ha^{-1} (from soybean) = 90 kg N ha^{-1}. The remaining 210 kg N ha^{-1} was applied in seven equal split doses of 30 kg N ha^{-1} at 10-day intervals after germination. Phosphorus and nitrogen were supplied through triple superphosphate and urea, respectively. All P for both crops under all treatments was applied as basal. Following local farmers' practice, total irrigation water applied was 600 mm for SM, 500 mm for SS, and 550 mm for SMi. All agronomic practices (sowing, weeding, harvesting, and threshing) were performed manually. For the DIm treatment, clear plastic mulch (0.01 mm thickness, 200 cm width) was laid over the crop rows before sowing and removed after crop harvest each year.

Insert Figure 4; Here

2.3 Measurements

Leaf area index (LAI) and dry matter accumulation (DMA) were measured at four key growth stages: for soybean at full bloom (60 ± 2 days after germination; DAG), full pod (95 ± 4 DAG), full seed (120 ± 2 DAG), and maturity stages, and for maize at tasseling (70 ± 2 DAG), blistering (90 ± 1 DAG), dough (120 ± 3 DAG), and maturity stages. At each growth stage, a 0.5 m^2 (0.40 m × 1.25 m) area was manually harvested from each treatment plot in every replication. LAI and DMA were quantified following previously reported protocols (Raza, Din, Shah, et al., 2024). N and P uptake were assessed at the same sampling stages used for LAI and DMA measurements by using the same dry matter samples collected at each stage using the Kjeldahl and Vanadomolybdate methods, respectively (Bremner, 1996; Xia et al., 2013). Furthermore, at the maturity of each crop, seed yield was measured by harvesting a 3.2 m^2 (0.4 m × 8 m) section from all treatments. Harvested samples were sun-dried for 15–20 days, then manually threshed. The nutrient uptake and crop yield were expressed in kg ha^{-1}, and DMA was expressed in t ha^{-1}.

Water use efficiency (WUE) of soybean and maize under different treatments was calculated using the previously published equation (Zhang et al., 1998):

$$WUE = \frac{SY}{TWU}$$

Where, SY is the seed yield of soybean or maize under the respective treatment, and TWU is the total water use estimated using the soil water balance approach (James, 1988). Moreover, to quantify the nutrient-use advantage of SMi relative to SS and SM, the partial land equivalent ratios for N and P uptake by soybean ($pLER_{NS}$ and $pLER_{PS}$) and maize ($pLER_{NM}$ and $pLER_{PM}$) were calculated using the following equations (Gou et al., 2018):

147 $$pLER_{NS} = \frac{NU_{IS}}{NU_{SS}}$$

148 $$pLER_{PS} = \frac{PU_{IS}}{PU_{SS}}$$

149 $$pLER_{NM} = \frac{NU_{IM}}{NU_{SM}}$$

150 $$pLER_{PM} = \frac{PU_{IM}}{PU_{SM}}$$

151

152 Where, the NU_{IS} and NU_{IM}, and PU_{IS} and PU_{IM} were the N and P uptake values for soybean and maize in SMi,
153 while the NU_{SS} and NU_{SM}, and PU_{SS} and PU_{SM} were the N and P uptake values for soybean and maize in SS and SM,
154 respectively. Then, the total land equivalent ratios (LER) for N (LER_N) and P (LER_P) of SMi were calculated using
155 the previously published equations (Gou et al., 2018):

156

157 $$Total\ LER_N = pLER_{NS} + pLER_{NM}$$

158 $$Total\ LER_P = pLER_{PS} + pLER_{PM}$$

159

160 Similar to the nutrient-use advantage, we first calculated the land use advantage of SMi over SS or SM by
161 estimating the partial land equivalent ratios for soybean ($pLER_{LS}$) and maize ($pLER_{LM}$) using the following equations
162 (Mead & Willey, 1980):

163

164 $$pLER_{LS} = \frac{SY_{IS}}{SY_{SS}}$$

165 $$pLER_{LM} = \frac{SY_{IM}}{SY_{SM}}$$

166

167 Where, the SY_{IS} and SY_{IM} were the seed yield of soybean and maize in SMi, while the SY_{SS} and SY_{SM} were the
168 seed yield of soybean and maize in SS and SM, respectively. Then, the total LER_L was determined using the following
169 equations (Mead & Willey, 1980):

170

171 $$Total\ LER_L = pLER_S + pLER_M$$

172

173 In addition, to estimate the water-use advantage of SMi over SS or SM, we first calculated the partial water
174 equivalent ratio of soybean ($pWER_S$) and maize ($pWER_M$) using the following equations (Mao et al., 2012):

175

176 $$pWER_S = \frac{WUE_{IS}}{WUE_{SS}}$$

177 $$pWER_M = \frac{WUE_{IM}}{WUE_{SM}}$$

Where, the WUE_{IS} and WUE_{IM} were the WUE of soybean and maize in SMi, while the WUE_{SS} and WUE_{SM} were the WUE of soybean and maize in SS and SM, respectively. Then, the total water equivalent ratio (WER) of SMi was calculated using the following equations (Mao et al., 2012):

$$Total\ WER = pWER_S + pWER_M$$

An economic analysis was conducted to evaluate the profitability of the different treatments. Production costs were estimated using local market prices and labor rates, and detailed cost components are presented in Table 1. Gross income was calculated based on crop yield and prevailing market prices, while net income and the benefit-to-cost ratio (BCR) were determined as follows:

$$Net\ income = Gross\ income - Total\ cost$$

$$BCR = \frac{Gross\ income}{Production\ cost}$$

All economic values were initially calculated in Chinese Yuan (RMB) and subsequently converted to US dollars (USD) using the average annual exchange rates. The exchange rates were 1 USD = 7.0 RMB in 2023, 7.1 RMB in 2024, and 7.1 RMB in 2025.

Table 1
Total costs (USD ha^{-1}) for each input/field operation required to grow spring maize and soybean during the 2023-2025 growing seasons in Zhangye, Gansu, China.

Inputs/field operations	2023	2024	2025	Mean
Maize seed	192	200	206	199
Soybean seed	140	146	150	145
Fungicide	36	38	39	38
Land preparation	119	122	126	122
Machine sowing	98	101	104	101
Weedicide	58	60	62	60
Plastic mulch film	150	142	145	146
Drip tape for maize	173	168	171	171
Drip tape for soybean	173	168	171	171
Fertilizers for maize	520	496	503	506
Fertilizers for soybean	299	285	289	291
Pesticides for maize	81	84	87	84
Pesticides for soybean	50	52	54	52
Irrigation for maize	490	505	505	500
Irrigation for soybean	490	505	505	500
Labor for maize	153	160	165	159
Labor for soybean	128	134	138	133
Maize harvesting + threshing	235	243	250	243
Soybean harvesting + threshing	196	202	208	202
Total for maize	2305	2319	2363	2329
Total for soybean	1937	1955	1991	1961

Note: All costs were obtained in the local currency (Chinese Yuan, RMB) and converted into US dollars (USD) using the annual average central parity exchange rate for each cropping year. One USD was trading at RMB 7.05 in 2023, 7.12 in 2024, and 7.14 in 2025.

2.4 Statistical analysis

Data were analyzed using a linear mixed-effect model (LMM) in SPSS version 29. Cropping system (three levels: SS; SM; and SMi), irrigation method (three levels: FI; DI; and DIm), and year (three levels: 2023, 2024, and 2025) were treated as fixed factors, while replication (block) was treated as a random factor. Because in this experiment, we employed a split plot design, cropping system was assigned to main plots and irrigation method to sub plots. The full model included the main effects of cropping system, irrigation method, and year, as well as their two-way and three-way interactions (cropping system × irrigation method, cropping system × year, irrigation method × year, and

cropping system × irrigation method × year). Complete model details and mixed-model ANOVA results are provided in Online Resources S1-S14. Data presented in tables and figures are means of three replications. Following significant treatment effects, mean comparisons were performed using Tukey's HSD test at $p < 0.05$.

3. Results

3.1 Growth performance

Mixed-model ANOVA indicated that cropping system (CS) and irrigation method (IM) were the main factors influencing LAI and DMA of soybean and maize (Online Resource S2-S5). For LAI, CS and IM had significant effects at all growth stages in both crops, whereas the year (Y) effect was significant only at maturity. Most interaction effects were non-significant, indicating relatively consistent treatment responses across the years. However, soybean LAI at maturity was significantly affected by the Y × CS and CS × IM interactions, while maize LAI at maturity was significantly affected by the CS × IM interaction. For DMA, CS and IM significantly affected both soybean and maize at all measured growth stages, whereas Y and interaction effects were generally non-significant. The temporal dynamics of LAI and DMA showed similar trends across treatments and years; LAI peaked at the full seed stage in soybean (Fig. 5a-h) and at the blistering stage in maize (Fig. 5i-p), whereas maximum DMA was recorded at the maturity stage in both crops, indicating continued biomass accumulation until maturity (soybean: Fig. 6a-h; and maize: Fig. 6i-p). Specifically, soybean and maize always achieved higher LAI and DMA in sole cropping (SS and SM, respectively) than in intercropping (SMi). However, under SMi, irrigation method DIm consistently improved LAI and DMA of both crops across all growth stages compared to irrigation methods DI and FI. For instance, at maturity under DIm, intercropped soybean attained 82% of sole soybean LAI (2.6 vs. 3.1) and 78% of sole soybean DMA (8.8 vs. 11.2 t ha^{-1}), while intercropped maize achieved 81% of sole maize LAI (2.9 vs. 3.6) and 73% of sole maize DMA (20.8 vs. 28.3 t ha^{-1}). In contrast, under FI, intercropped soybean attained only 65% of sole soybean LAI (1.5 vs. 2.3) and 71% of sole soybean DMA (5.8 vs. 8.1 t ha^{-1}), while intercropped maize achieved 61% of sole maize LAI (1.8 vs. 2.9) and 69% of sole maize DMA (15.1 vs. 21.8 t ha^{-1}). Overall, these results clearly indicate that DIm reduced intercropping-induced growth suppression, allowing intercrops to recover 73–82% of their corresponding sole-crop growth at maturity.

Insert Figures 5 and 6; Here

3.2 Nutrient uptake and nutrient use advantage

Mixed-model ANOVA indicated that CS and IM were the dominant factors affecting N and P uptake of soybean and maize (Online Resources S6-S9). For N uptake, CS and IM had significant effects at all growth stages in both crops. The Y effect was significant for soybean at all stages and for maize at tasseling, blistering, and maturity stages, but not at the dough stage. Most interaction effects for soybean N uptake were non-significant, except for Y × CS at the

full seed stage and Y × IM at maturity. In maize, N uptake showed greater sensitivity to interaction effects, with significant Y × CS effects at tasseling and dough stages, Y × IM at maturity, CS × IM at blistering and maturity stages, and Y × CS × IM at blistering. For P uptake, CS and IM significantly affected both soybean and maize at all measured growth stages, whereas Y and all interaction effects were non-significant. These results indicate that P uptake was mainly controlled by CS and IM, while N uptake was additionally influenced by year and selected interaction effects, particularly in maize. On average, over the three years, soybean N uptake (Fig. 7a–h) and P uptake (Fig. 7i–p), as well as maize N uptake (Fig. 8a–h) and P uptake (Fig. 8i–p), were higher under SS and SM, respectively, than under SMi across all growth stages; and for both crops, DIm resulted in the highest nutrient (N and P) uptake, followed by DI and FI. For maize, the mean highest N uptake (191.8, 215.1, 249.3, and 315.2 kg ha^{-1}) and P uptake (18.4, 43.5, 57.9, and 68.7 kg ha^{-1}) at the tasseling, blistering, dough, and maturity stages, respectively, were observed under SM with DIm. In contrast, the mean lowest N uptake (110.5, 119.7, 137.1, and 126.9 kg ha^{-1}) and P uptake (7.4, 18.9, 23.4, and 18.3 kg ha^{-1}) at the respective stages were recorded under SMi with FI. For soybean, the mean maximum N uptake (101.3, 145.9, 193.7, and 220.6 kg ha^{-1}) and P uptake (5.7, 13.8, 23.1, and 27.4 kg ha^{-1}) at the full bloom, full pod, full seed, and maturity stages, respectively, were noted under SS with DIm. Whereas, the mean lowest N uptake (39.5, 65.4, 73.7, and 82.5 kg ha^{-1}) and P uptake (2.2, 5.9, 10.2, and 11.5 kg ha^{-1}) at the respective stages were recorded under SMi with FI. Overall, these findings indicate that both CS and IM strongly regulated nutrient uptake dynamics in soybean and maize, with DIm improving nutrient acquisition under both sole and intercropping systems.

Insert Figures 7 and 8; Here

Mixed-model ANOVA indicated that IM significantly affected partial LER_N and LER_P of maize and soybean, as well as total LER_N and LER_P (Online Resource S10). The Y effect was significant for maize partial LER_N, soybean partial LER_P, total LER_N, and LER_P, but non-significant for soybean partial LER_N and maize partial LER_P. The Y × IM interaction was non-significant for all indices except for total LER_P, indicating that irrigation effects on nutrient-based land-use advantage were generally stable across years, with some year-dependent variation in total phosphorus-based LER. Generally, irrespective of irrigation method, the total LER values for N and P were always higher than one, indicating a nutrient-use advantage of SMi over SM or SS (Table 2). On average, intercropped soybean and maize exhibited the highest $pLER_N$ (soybean: 0.75; maize: 0.81) and $pLER_P$ (soybean: 0.84; maize: 0.76) values under DIm, while both crops had the lowest $pLER_N$ (soybean: 0.64; maize: 0.62) and $pLER_P$ (soybean: 0.66; maize: 0.56) values under FI, respectively (Table 2). Overall, when compared under the same irrigation method, total mean LER_N and LER_P values for DIm were 1.56 and 1.61, respectively, which were 9% and 14% higher than those under DI (LER_N: 1.43; LER_P: 1.41) and 24% and 31% higher than those under FI (LER_N: 1.26; LER_P: 1.23). Thus, under DIm, intercropping utilized 56-61% more N and P per unit land than sole cropping; under DI, the advantage was 41-43%; and under FI, it was 23-26%. These results demonstrate that SMi utilized N and P more efficiently than sole crops across all irrigation methods, with DIm providing the greatest relative nutrient use advantage compared to other irrigation methods.

Table 2

Partial land equivalent ratio for nitrogen ($pLER_N$) and phosphorus ($pLER_P$) of soybean and maize, and total land equivalent ratio (LER) for nitrogen (LER_N) and phosphorus (LER_P) in soybean/maize intercropping as influenced by different irrigation methods.

Irrigation methods	$pLER_N$						Total LER_N			$pLER_P$						Total LER_P		
	Soybean			Maize						Soybean			Maize					
	2023	2024	2025	2023	2024	2025	2023	2024	2025	2023	2024	2025	2023	2024	2025	2023	2024	2025
FI	0.60c	0.64c	0.66c	0.63c	0.64c	0.59c	1.23c	1.29c	1.26c	0.70c	0.62c	0.67c	0.58c	0.55c	0.55c	1.28c	1.17c	1.23c
DI	0.67b	0.72b	0.70b	0.72b	0.73b	0.74b	1.39b	1.46b	1.44b	0.79b	0.76b	0.77b	0.63b	0.64b	0.63b	1.42b	1.40b	1.40b
DIm	0.74a	0.75a	0.76a	0.79a	0.83a	0.80a	1.53a	1.59a	1.56a	0.86a	0.83a	0.85a	0.74a	0.78a	0.76a	1.60a	1.60a	1.61a

FI: flood irrigation; DI: drip irrigation without plastic mulch; and DIm: drip irrigation with plastic mulch. Different lowercase letters within each column indicate significant differences among treatments at $p < 0.05$ (Tukey's HSD test).

3.3 Crop yield and land use advantage

Mixed-model ANOVA showed that CS and IM significantly affected seed yield of maize and soybean, whereas the Y effect was non-significant for both crops (Online Resource S11). In maize, seed yield was also significantly influenced by Y × CS and CS × IM interactions, while Y × IM and Y × CS × IM were non-significant. In soybean, only the Y × IM interaction was significant, whereas Y × CS, CS × IM, and Y × CS × IM were non-significant. These results indicate that seed yield was mainly determined by CS and IM, with crop-specific interaction responses. Overall, maize consistently produced higher yields than soybean across all treatments. Consistent with the trends observed for growth performance and nutrient uptake, soybean and maize achieved their highest yields under SS and SM, respectively, compared with their yields under SMi, regardless of irrigation method (Table 3). However, under intercropping, the relative yield performance of both crops improved with improved irrigation management (DIm). On average, intercropped soybean (1658.6 kg ha^{-1} with FI, 2335.8 kg ha^{-1} with DI, and 2751.9 kg ha^{-1} with DIm) achieved 62%, 68%, and 72% of sole soybean yield (FI: 2684.8 kg ha^{-1}; DI: 3419.6 kg ha^{-1}; DIm: 3831.9 kg ha^{-1}). Similarly, intercropped maize (6765.3 kg ha^{-1} with FI, 9380.8 kg ha^{-1} with DI, and 11553.8 kg ha^{-1} with DIm) achieved 59%, 71%, and 75% of sole maize yield (FI: 11528.1 kg ha^{-1}; DI: 13287.7 kg ha^{-1}; DIm: 15484.5 kg ha^{-1}) (Table 3). Notably, compared with FI, DIm increased sole soybean yield by 43% and intercropped soybean yield by 66%; similarly, it increased sole maize yield by 34% and intercropped maize yield by 71%, indicating that DIm not only improved absolute seed yield but also reduced the yield gap between intercropping and sole cropping systems, particularly for maize.

Mixed-model ANOVA indicated that IM significantly affected partial LER of both maize and soybean, as well as total LER_L (Online Resource S12). The Y effect was significant for maize partial LER and total LER_L, but non-significant for soybean partial LER. The Y × IM interaction was non-significant for all indices, indicating that irrigation effects on yield-based land-use advantage were relatively stable across years. Total LER_L values of SMi ranged from 1.19 to 1.49, indicating a clear land use advantage of intercropping over sole cropping systems (Table 4). Across irrigation methods, total LER_L values were always higher under DIm than under DI and FI. On average, over the three years, the $pLER_L$ values of soybean and maize ranged from 0.60 to 0.77 across treatments. Notably, under FI, soybean exhibited a higher $pLER_{LS}$ (0.62) than maize's $pLER_{LM}$ (0.59), whereas under DI and DIm, maize achieved higher $pLER_{LM}$ values (0.71 and 0.75, respectively) than soybean's $pLER_{LS}$ (0.68 and 0.72, respectively) (Table 4). Overall, across the three years, total LER_L values under DIm were 1.48, 1.49, and 1.43 in 2023, 2024, and 2025, respectively, which were 5–6% higher than those under DI and 20–23% higher than those under FI, suggesting that the land-use advantage of soybean/ maize intercropping was closely associated with irrigation method (Table 4).

Table 3

Seed yield (kg ha^{-1}) of soybean and maize as influenced by different irrigation methods under soybean/maize intercropping and sole cropping systems.

Irrigation methods	Intercropping						Sole cropping					
	Soybean			Maize			Soybean			Maize		
	2023	2024	2025	2023	2024	2025	2023	2024	2025	2023	2024	2025
FI	1659.7c	1615.5c	1700.6c	6823.2c	6575.7c	6896.8c	2690.9c	2539.9c	2823.6c	11237.3c	11516.4c	11830.7c
DI	2185.3b	2517.4b	2304.7b	9598.4b	9483.8b	9059.5b	3239.6b	3594.1b	3425.1b	13142.2b	13393.6b	13327.4b
DIm	2646.9a	2896.6a	2712.3a	11822.7a	11490.9a	11347.8a	3750.9a	3946.2a	3798.7a	15310.6a	15245.6a	15897.2a

FI: flood irrigation; DI: drip irrigation without plastic mulch; and DIm: drip irrigation with plastic mulch. Different lowercase letters within each column indicate significant differences among treatments at $p < 0.05$ (Tukey's HSD test).

3.4 Water use efficiency and water use advantage

Mixed-model ANOVA showed that CS and IM significantly affected WUE of maize and soybean, whereas Y had a non-significant effect on both crops (Online Resource S13). The interaction between Y × CS for WUE was non-significant in both crops, whereas the Y × IM interaction was significant only for soybean. In contrast, the CS × IM interaction significantly affected WUE of both maize and soybean, while the Y × CS × IM was non-significant for both crops. Averaged across the three years, the highest WUE of soybean (6.3 kg ha^{-1} mm^{-1}) and maize (21.4 kg ha^{-1} mm^{-1}) was observed in SS and SM under DIm, respectively, whereas the lowest WUE of soybean (2.4 kg ha^{-1} mm^{-1}) and maize (9.1 kg ha^{-1} mm^{-1}) was recorded in SMi with FI (Table 5). Overall, compared with FI, DIm increased the WUE of soybean by 47% under SS and by 77% under SMi, and it increased the WUE of maize by 38% under SM and by 75% under SMi (Table 5).

Mixed-model ANOVA indicated that Y and IM significantly affected partial WER of both maize and soybean, as well as total WER (Online Resource S14). The Y × IM interaction was non-significant for all indices, indicating that the effect of irrigation method on water-equivalent ratio was relatively stable across years. When averaged across the three years, the maximum $pWER_S$ (0.68) and $pWER_M$ (0.75) were measured with DIm, while the minimum $pWER_S$ (0.57) and $pWER_M$ (0.59) were recorded with FI (Table 4). Notably, across the three years, the mean total WER values under FI, DI, and DIm were 1.15, 1.34, and 1.43, respectively, and all were greater than one, similar to total LER_N, LER_P, and LER_L, indicating that SMi had an advantage in using applied water more efficiently than SS or SM (Table 4). For instance, compared with FI and DI, DIm increased total WER by 24% and 7%, respectively, suggesting that the water use advantage in intercropping was strongly influenced by irrigation methods.

Table 4

Partial land equivalent ratio for land ($pLER_L$) and partial water equivalent ratio (pWER) of soybean and maize, and total land equivalent ratio (LER) and water equivalent ratio (WER) in soybean/maize intercropping as influenced by different irrigation methods.

Irrigation methods	$pLER_L$						Total LER_L			pWER						Total WER		
	Soybean			Maize						Soybean			Maize					
	2023	2024	2025	2023	2024	2025	2023	2024	2025	2023	2024	2025	2023	2024	2025	2023	2024	2025
FI	0.62b	0.64b	0.60b	0.61b	0.57b	0.58b	1.22c	1.21b	1.19b	0.56b	0.58b	0.55b	0.61b	0.57b	0.58b	1.17c	1.16b	1.14c
DI	0.67ab	0.70ab	0.67a	0.73a	0.71a	0.68a	1.41b	1.41a	1.35a	0.63ab	0.65ab	0.62a	0.73a	0.71a	0.68a	1.36b	1.36a	1.30b
DIm	0.71a	0.73a	0.71a	0.77a	0.75a	0.71a	1.48a	1.49a	1.43a	0.67a	0.70a	0.68a	0.77a	0.75a	0.71a	1.44a	1.45a	1.39a

FI: flood irrigation; DI: drip irrigation without plastic mulch; and DIm: drip irrigation with plastic mulch. Different lowercase letters within each column indicate significant differences among treatments at $p < 0.05$ (Tukey's HSD test).

Table 5

Water use efficiency (kg ha^{-1} mm^{-1}) of soybean and maize as influenced by different irrigation methods under soybean/maize intercropping and sole cropping systems.

Irrigation methods	Intercropping						Sole cropping					
	Soybean			Maize			Soybean			Maize		
	2023	2024	2025	2023	2024	2025	2023	2024	2025	2023	2024	2025
FI	2.5c	2.4c	2.4c	9.4c	8.9c	9.1c	4.4c	4.1c	4.4c	15.5c	15.5c	15.6c
DI	3.4b	3.8b	3.4b	13.4b	12.9b	12.1b	5.4b	5.8b	5.4b	18.3b	18.3b	17.7b
DIm	4.2a	4.5a	4.2a	16.7a	15.9a	15.4a	6.4a	6.5a	6.1a	21.6a	21.1a	21.6a

FI: flood irrigation; DI: drip irrigation without plastic mulch; and DIm: drip irrigation with plastic mulch. Different lowercase letters within each column indicate significant differences among treatments at $p < 0.05$ (Tukey's HSD test).

3.5 Economic returns

The production cost of soybean and maize under sole and intercropping systems varied with irrigation methods. Averaged across the three years, total production costs under FI, DI, and DIm for SMi were 2122, 2292, and 2436 USD ha^{-1}, respectively, which was 9-11% higher than the corresponding costs for SS (1860, 2031, and 2176 USD ha^{-1}) and 3-4% higher than those for SM (2008, 2178, and 2324 USD ha^{-1}) (Table 6). However, under FI, sole soybean was not profitable and produced negative net income in all three years (mean: -235 USD ha^{-1}), with BCR values below 1 (0.87 in 2023, 0.81 in 2024, and 0.86 in 2025), indicating that production costs consistently exceeded gross income. Even under DI and DIm, sole soybean remained only marginally profitable, with mean net incomes of just 36 and 142 USD ha^{-1}, respectively, considerably lower than those of SM or SMi under the same irrigation methods. In contrast, SM and SMi were profitable across all irrigation methods, with SMi-DIm achieving the highest net income (SM: 2769 USD ha^{-1}; SMi: 3077 USD ha^{-1}) and BCR (SM: 2.19; SMi: 2.29) among all treatments (Table 6). Overall, these results indicate that SMi-DIm increased net farm income while conserving water and improving resource-use efficiency compared with SS and SM under FI.\

Table 6.
Total expenditure, gross income, net income, and benefit cost ratio (BCR) of maize and soybean under soybean/maize intercropping (SMi), sole soybean (SS), and sole maize (SM) cropping systems. All values are given in USD ha^{-1}.

Cropping systems	Irrigation methods	Expenditure			Gross income			Net income			BCR		
		2023	2024	2025	2023	2024	2025	2023	2024	2025	2023	2024	2025
SMi	FI	2049	2080	2122	3775	2873	3052	1726	793	930	1.84	1.38	1.44
	DI	2221	2248	2292	5213	4255	4050	2992	2007	1758	2.35	1.89	1.77
	DIm	2371	2390	2436	6392	5064	4973	4021	2674	2537	2.70	2.12	2.04
SS	FI	1835	1856	1889	1757	1498	1621	-78	-358	-268	0.96	0.81	0.86
	DI	2008	2024	2060	2115	2120	1966	107	96	-94	1.05	1.05	0.95
	DIm	2158	2166	2205	2449	2327	2180	291	161	-25	1.13	1.07	0.99
SM	FI	1977	2004	2042	4433	3364	3561	2456	1360	1519	2.24	1.68	1.74
	DI	2150	2172	2213	5185	3912	4012	3035	1740	1799	2.41	1.80	1.81
	DIm	2300	2314	2358	6040	4453	4785	3740	2139	2427	2.63	1.92	2.03

FI: flood irrigation; DI: drip irrigation without plastic mulch; and DIm: drip irrigation with plastic mulch. The market price for maize was 395 USD t^{-1} in 2023, 292 USD t^{-1} in 2024, and 301 USD t^{-1} in 2025; and for soybean, it was 653 USD t^{-1} in 2023, 590 USD t^{-1} in 2024, and 574 USD t^{-1} in 2025.

4. Discussion

This study examined the effects of different irrigation methods (FI, DI, and DIm) and cropping systems (sole and intercropping) on the growth, nutrient uptake, and yield of soybean and maize under arid-irrigated conditions. Results revealed that both crops always achieved the highest yield and economic returns under DIm. However, at the system level, SMi (soybean/maize intercropping) outperformed the respective sole cropping systems in water, nutrient, and land-use efficiency, as indicated by WER and LER values, which were consistently above 1. This demonstrates a substantial intercropping advantage in achieving higher relative crop yields and economic returns while conserving resources. Importantly, our findings further indicate that both crops can be cultivated simultaneously within the same season, especially in areas where climatic constraints currently permit only one crop annually. Therefore, we advocate intercropping combined with DIm for cereal (e.g., maize) and legume (e.g., soybean) production in arid-irrigated regions, as this mixture has shown enhanced productivity and resource-use efficiency in varied agro-ecological environments globally (Duchene et al., 2017; Feng et al., 2020; Iqbal et al., 2018; Li et al., 2020; Raza et al., 2021).

Crop growth and productivity are typically measured through key crop indicators such as LAI, DMA, and seed yield (Raza et al., 2021). These parameters are directly influenced by the amount and method of irrigation, because water availability regulates root development and the root zone microenvironment, which in turn affects water and nutrient use efficiency (Kang et al., 2000). In the present study, different irrigation methods significantly affected the LAI, DMA, and yield of soybean and maize; both crops exhibited the highest values under DIm, followed by DI and FI. This improvement under DIm can be attributed to its ability to conserve moisture, enhance nutrient availability in the rhizosphere, and optimize soil temperature, all of which improve crop physiological processes (Li et al., 2017; Wang et al., 2024). Consequently, DIm enhanced resource acquisition, leading to better canopy development, greater DMA, and more efficient translocation of assimilates to seeds, ultimately resulting in higher crop yields compared to DI and FI (Li et al., 2023; Wang et al., 2011). On the contrary, lower LAI, DMA, and crop yield values were observed under DI and FI, probably due to increased water losses through evapotranspiration and poor water management, respectively; (a) as in DI, the absence of plastic mulch possibly led to higher surface evaporation losses and suboptimal soil temperature regulation, reducing water and nutrient uptake, which are important for achieving higher LAI, DMA, and yield values, and (b) in FI, uneven moisture distribution and prolonged soil saturation may have reduced root respiration and limited nutrient uptake, ultimately limiting root function and plant growth (Wang et al., 2024; Wang et al., 2021; Yang et al., 2023). In addition to irrigation methods, the cropping systems also affect plant growth and yield (Feng et al., 2019; Raza et al., 2021). For instance, in sole cropping, plants of the same species compete intensively for similar resource niches (strong intraspecific competition), whereas intercropping alleviates such competition through interspecific complementarities and spatio-temporal niche differentiation (Duchene et al., 2017; Iqbal et al., 2018; Wezel et al., 2014). Consistent with previous findings, our study confirms that crop combination and growth stage synchronization between soybean and maize under SMi enhance facilitative interactions, reduce interspecific competition, and promote asymmetric resource allocation, thereby improving the growth and yield of both species (Brooker et al., 2015; Iqbal et al., 2018; Lithourgidis et al., 2011; Raza et al., 2025; Wezel et al., 2020).

Taken together, these results imply that integrating SMi with DIm is a viable and productive strategy for enhancing agricultural productivity in arid-irrigated regions.

Water and nutrient uptake are tightly coupled processes that fundamentally influence crop growth, physiological functioning, yield and components (Cheng et al., 2023; Gitari et al., 2020). Several previous studies have evaluated water and nutrient uptake dynamics in soybean and maize under different cropping systems (Fan et al., 2020; Raza et al., 2019; Raza et al., 2021; Zhang et al., 2021). However, to the best of our knowledge, no prior research has simultaneously examined these processes in relation to both cropping systems and irrigation methods. In this context, the present study offers novel insights, demonstrating that the WUE and nutrient (N and P) uptake were significantly enhanced under DIm compared to DI and FI, regardless of the cropping system. The improved WUE and nutrient uptake observed under DIm can be attributed to a combination of interrelated biophysical and microclimatic factors (Wang et al., 2024). Plastic mulch combined with drip irrigation created a stable rhizosphere environment by enhancing soil moisture retention, controlling weeds, and moderating soil temperature fluctuations, as previously reported (Wang et al., 2021; Zhang et al., 2023; Zhang et al., 2022; Zhang et al., 2021). These conditions supported sustained root growth and function and facilitated greater synchronization between water supply and nutrient demand throughout the crop cycle (Wang et al., 2024; Wang et al., 2011). Moreover, localized and frequent water delivery via drip lines ensured better hydration of the root zone, enhancing nutrient solubility and availability, while the mulch layer reduced evaporative losses, leading to a more efficient water budget (Wang et al., 2024). These results are consistent with the concept of "nutrient capture efficiency," whereby optimal soil moisture facilitates greater mass flow and diffusion of nutrients toward active root surfaces (Ullah et al., 2019; Wang et al., 2024). The continuous water supply under DIm also likely prevented nutrient leaching and allowed better root–soil contact, increasing nutrient uptake efficiency (Wang et al., 2024). These interactions resulted in higher uptake of water and nutrients, translating into improved crop performance and resource use efficiency (Yin et al., 2024).

Similarly, SMi consistently outperformed their respective sole cropping systems (SM and SS) in utilizing the available resources such as land, water, and nutrients (N and P). This can be explained by well-established interspecific facilitative mechanisms, including complementary root architecture, spatio-temporal niche differentiation, and enhanced nutrient bioavailability (Ahmed et al., 2018; Gitari et al., 2020; Iqbal et al., 2018). In addition, soybean, being a legume, likely contributed to improved N and P dynamics through atmospheric nitrogen fixation and the release of root exudates or microbial interactions, respectively, which subsequently enhanced nutrient availability for maize (Duchene et al., 2017; Fan et al., 2020; Iqbal et al., 2018). Meanwhile, maize-with its deeper root system-accessed subsoil N and P reserves beyond the reach of soybean, thereby increasing the total nutrient uptake of the system (Ahmed et al., 2018; Fan et al., 2020). These spatial and temporal complementarities reduce interspecific competition and enhance resource-use efficiency, and improve both WUE and nutrient acquisition (Ahmed et al., 2018; Gitari et al., 2020; Raza, Din, Shah, et al., 2024). Furthermore, the benefits of SMi were further amplified under the DIm irrigation method, where favorable soil moisture and temperature conditions likely enhanced microbial activity and nutrient cycling (Kapoor et al., 2022; Wang et al., 2024; Zhang et al., 2022). Higher WUE in SMi-DIm can also be attributed to reduced transpiration rates under mulch, greater canopy coverage, and more efficient water partitioning among component crops, allowing better utilization of limited water resources (Kapoor et al., 2022; Wang et al., 2024).

The root systems of maize and soybean may have explored different soil zones both vertically and horizontally, allowing for greater water and nutrient capture without direct competition (Feng et al., 2019; Raza et al., 2021). This synergy enhances the overall ecological efficiency of the system by optimizing key physiological processes such as water uptake, photosynthesis, and nutrient translocation (Fan et al., 2020; Feng et al., 2020; Wang et al., 2024). It is noteworthy that although the aggregate growth parameters (e.g., LAI and DMA), nutrient uptake, and crop yields for SMi were lower than those of SS and SM under all irrigation methods, this was primarily due to the reduced planting density in intercropping. Each component crop in the SMi system was sown at 50% of its sole crop density, thereby receiving only half the land, water, and nutrient inputs. Nevertheless, on a relative basis, both crops consistently exhibited higher LAI, DMA, nutrient uptake, and yield under SMi compared to SS and SM. This pattern indicates that reduced intraspecific competition in SMi facilitated greater per-plant access to light, water, and nutrients, enhancing individual performance and compensating for reduced population density (Fan et al., 2020; Feng et al., 2019; Raza et al., 2019). Such compensatory growth reflects the resource partitioning and plasticity inherent in intercropping systems, where each species adjusts its physiology and morphology in response to neighboring plants (Iqbal et al., 2018). These interactions not only improve individual plant performance but also elevate system-level efficiency, determined as LER for N, P, land, and WER, by maximizing the exploitation of available and environmental resources (Ahmed et al., 2018; Brooker et al., 2015; Hauggaard-Nielsen & Jensen, 2005). Collectively, the synergistic effects of intercropping and drip irrigation with mulch promote an integrated soil–plant–atmosphere continuum that enhances both water and nutrient dynamics. Improved root–soil contact, optimal moisture conditions, and minimized evaporative losses all contribute to superior WUE and nutrient uptake under the SMi-DIm combination, which finally enhanced the intercropping advantage in utilizing applied/available resources (water, nutrient, land) over their respective sole cropping systems, as previously reported (Feng et al., 2019; Gitari et al., 2020; Li et al., 2009; Li et al., 2017; Raza et al., 2021).

The adoption of any new innovation in agricultural production hinges on its economic viability and profitability, particularly in resource-intensive farming systems, where farmers are keenly focused on achieving high economic returns (Feng et al., 2020; Raza, Din, Gul, et al., 2024). Given the risk-averse nature of farming communities, especially in regions with volatile agricultural markets and price fluctuations, sole cropping remains dominant due to its yield and market stability (Huang et al., 2015; Manevska-Tasevska et al., 2024; Raza, Din, Shah, et al., 2024). However, intercropping systems that increase gross margin, land-use efficiency, and employment opportunities can serve as a sustainable intensification strategy, particularly for smallholder farmers who rely on agriculture for both household food security and income generation (Huang et al., 2015; Raza et al., 2021). Our findings confirmed that SMi with DIm significantly improved net income and overall system productivity compared to their respective sole cropping systems. For instance, SMi under DIm, increased total net income by 95% relative to sole soybean, and by 10% relative to sole maize, indicating that soybean intercropping with maize have significant growth potential to increase the farm-income than traditional sole cropping systems (Huang et al., 2015; Manevska-Tasevska et al., 2024). However, it is equally important to note that sole soybean cultivation under FI consistently produced negative net income across all three years, indicating that production costs exceeded gross income. Even under the more advanced DI and DIm systems, sole soybean remained only marginally profitable. This poor economic performance is not unique

to our experimental site but reflects a broader global challenge for legume production, as legume prices and production costs are highly volatile, particularly in intensive sole cropping systems. For example, in our study region, the soybean price fell from 652 USD t^{-1} in 2023 to 574 USD t^{-1} in 2025, a 12% decline that erased profits for most sole soybean growers. Consequently, farmers in arid-irrigated regions are reluctant to grow sole soybean without substantial government subsidies or price support mechanisms. This real-world constraint highlights the practical value of intercropping: by combining soybean with maize, farmers secure the stable income from maize (which remains profitable under all irrigation methods) while the additional soybean yield provides a buffer against market downturns. Thus, SMi-DIm not only improves resource use efficiency but also enhances economic resilience to price volatility, a critical advantage that sole cropping systems cannot offer. Specifically, the economic gains of SMi-DIm primarily arise from three factors: (i) enhanced land productivity through overyielding, where SMi-DIm consistently achieves higher total yields compared to other irrigation methods and sole cropping systems, thus generating additional grain revenue without the need for additional land; (ii) improved resource-use efficiency, due to the optimal irrigation management with mulch, which leads to higher yields with reduced water and fertilizer inputs compared to traditional methods, thereby lowering input costs; and (iii) increased economic stability and resilience through diversified production, which mitigates the risks associated with market fluctuations and environmental variability, as seen in arid regions in previous studies (Fan et al., 2020; Feng et al., 2019; Raza et al., 2021). Taken together, these results demonstrate that SMi-DIm is a viable and scalable strategy for enhancing resource use efficiencies and economic returns, while promoting environmental sustainability under arid-irrigated conditions.

5. Conclusion

Based on a three-year field experiment under arid-irrigated conditions, we compared the agronomic performance, resource-use efficiency, and economic viability of soybean/maize intercropping under different irrigation methods with their respective sole cropping systems. Our results demonstrated that intercropping with drip irrigation and plastic mulch significantly enhanced crop growth, nutrient uptake, seed yield, and economic returns while improving water, nutrient, and land use efficiencies compared to sole cropping systems. These benefits were largely driven by the integration of SMi and DIm, which improved resource capture and use efficiency by enhancing water and nutrient availability, reducing evaporation losses, and improving nutrient cycling in the rhizosphere. This combination enhanced land productivity and economic profitability, highlighting the potential of intercropping systems under resource-limited conditions. Overall, these findings have important implications for arid and semi-arid regions, where water scarcity and nutrient limitations constrain crop productivity. Therefore, the SMi-DIm system represents a promising strategy for improving resource-use efficiency and increasing crop productivity per unit of land, water, and nutrient input. However, further research is needed to evaluate the long-term impacts of crop intensification on soil health under drip irrigation combined with plastic mulch, the adaptability of legume-based intercropping systems across different agroecological conditions, and the optimization of planting density, spatial configuration, and irrigation management practices.

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Figure 1
Soybean/maize intercropping (SMi) demonstration in China and Pakistan: (a) intercrops at the vegetative growth stage under SMi with drip irrigation and plastic mulch in Zhangye, Gansu, China; (b) intercrops at the reproductive growth stage under SMi with flood irrigation in Bahawalpur, Punjab, Pakistan. (Photos: (a) Wang Zhiqi; (b) Muhammad Ali Raza).

Figure 2
Daily maximum and minimum temperature (a-c), rainfall (d-f), and solar radiation (photosynthetically active radiation, PAR; d-f) during the experimental period from March 2023 to October 2025.

Figure 3
Schematic diagram of the narrow-wide-row configuration used in soybean/maize intercropping system. Total strip width is 200 cm, consisting of a 40 cm soybean narrow-strip (2 rows at 40 cm spacing) and a 40 cm maize narrow-strip (2 rows at 40 cm spacing), separated by a 60 cm wide-strip to facilitate field operations and reduce interspecific competition.

Figure 4
Crop growth periods for soybean (green) and maize (brown) under intercropping and sole cropping systems. Co-growth period is the number of days when both soybean and maize grow together under intercropping system.

Figure 5
Leaf area index (a-h) and dry matter (i-p) of soybean at full bloom (FB), full pod (FP), full seed (FS), and maturity stage (MS) as influenced by different irrigation methods under soybean/maize intercropping and sole cropping systems. FI: flood irrigation; DI: drip irrigation without plastic mulch; and DIm: drip irrigation with plastic mulch. Different lowercase letters within each column indicate significant differences among treatments at $p < 0.05$ (Tukey's HSD test).

Figure 6
Leaf area index (a-h) and dry matter (i-p) of maize at tasseling stage (TS), blistering stage (BS), dough stage (DS), and maturity stage (MS) as influenced by different irrigation methods under soybean/maize intercropping and sole cropping systems. FI: flood irrigation; DI: drip irrigation without plastic mulch; and DIm: drip irrigation with plastic mulch. Different lowercase letters within each column indicate significant differences among treatments at $p < 0.05$ (Tukey's HSD test).

Figure 7
Nitrogen uptake (NU; a-h) and phosphorus uptake (PU; i-p) of soybean at full bloom (FB), full pod (FP), full seed (FS), and maturity stage (MS) as influenced by different irrigation methods under soybean/maize intercropping and sole cropping systems. FI: flood irrigation; DI: drip irrigation without plastic mulch; and DIm: drip irrigation with plastic mulch. Different lowercase letters within each column indicate significant differences among treatments at $p < 0.05$ (Tukey's HSD test).

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Supplementary Information

Online Resource 1 Mixed-model ANOVA complete model details and overall results.

Online Resource 2 Mixed-model ANOVA results for leaf area index (LAI) of soybean.

Online Resource 3 Mixed-model ANOVA results for leaf area index (LAI) of maize.

Online Resource 4 Mixed-model ANOVA results for dry matter accumulation (DMA) of soybean.

Online Resource 5 Mixed-model ANOVA results for dry matter accumulation (DMA) of maize.

Online Resource 6 Mixed-model ANOVA results for nitrogen (N) uptake of soybean.

Online Resource 7 Mixed-model ANOVA results for nitrogen (N) uptake of maize.

Online Resource 8 Mixed-model ANOVA results for phosphorus (P) uptake of soybean.

Online Resource 9 Mixed-model ANOVA results for phosphorus (P) uptake of maize.

Online Resource 10 Mixed-model ANOVA results for partial LER~N~ and LER~P~.

Online Resource 11 Mixed-model ANOVA results for seed yield of soybean and maize.

Online Resource 12 Mixed-model ANOVA results for partial land equivalent ratio (LER~L~).

Online Resource 13 Mixed-model ANOVA results for water use efficiency (WUE) of soybean and maize.

Online Resource 14 Mixed-model ANOVA results for partial water equivalent ratio (pWER) and total water equivalent ratio (WER).



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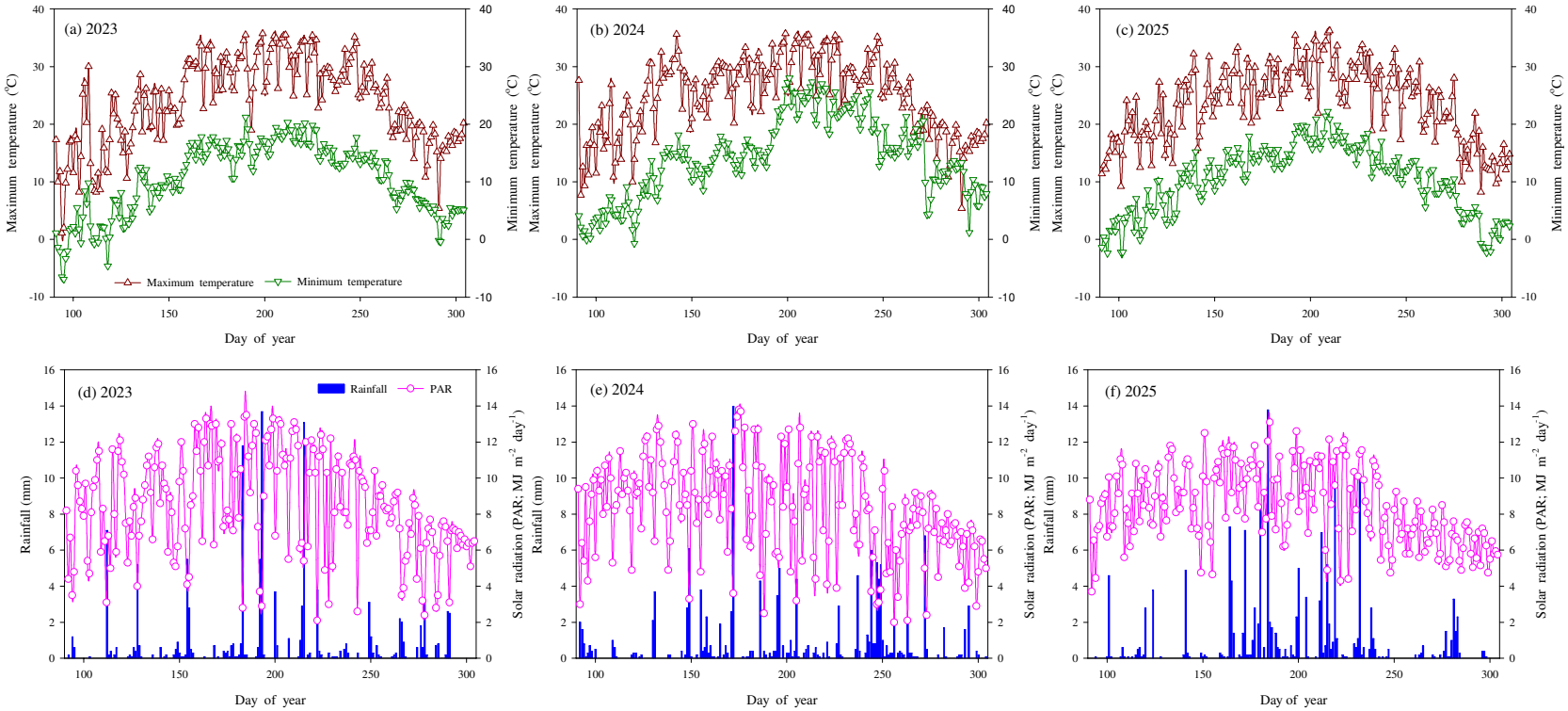


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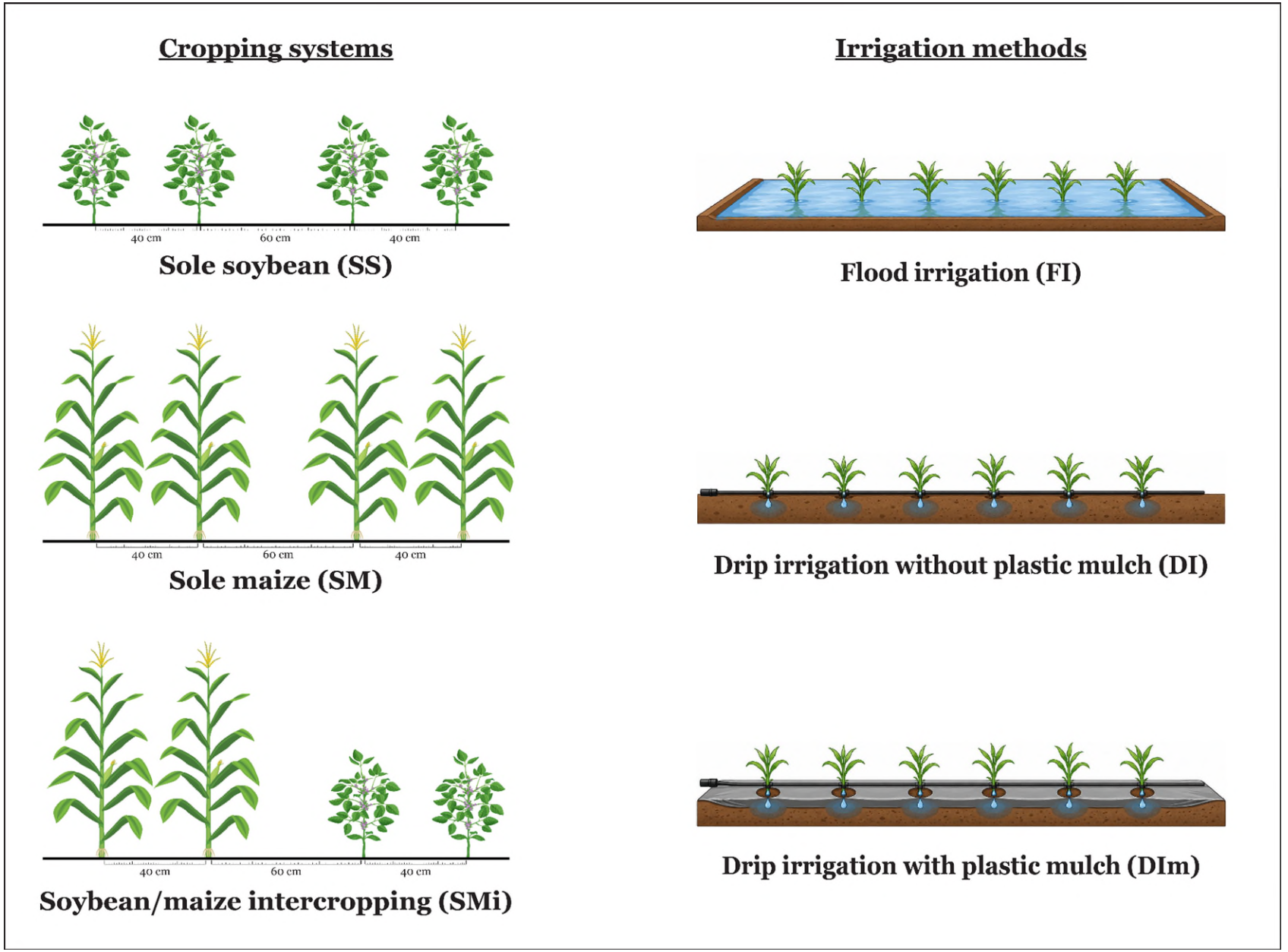


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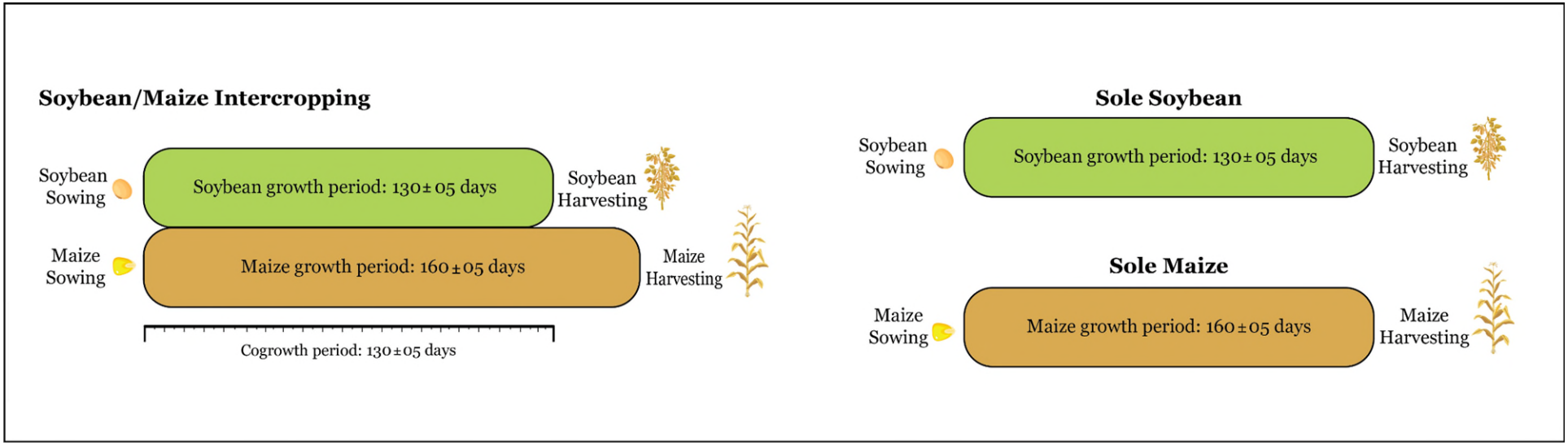


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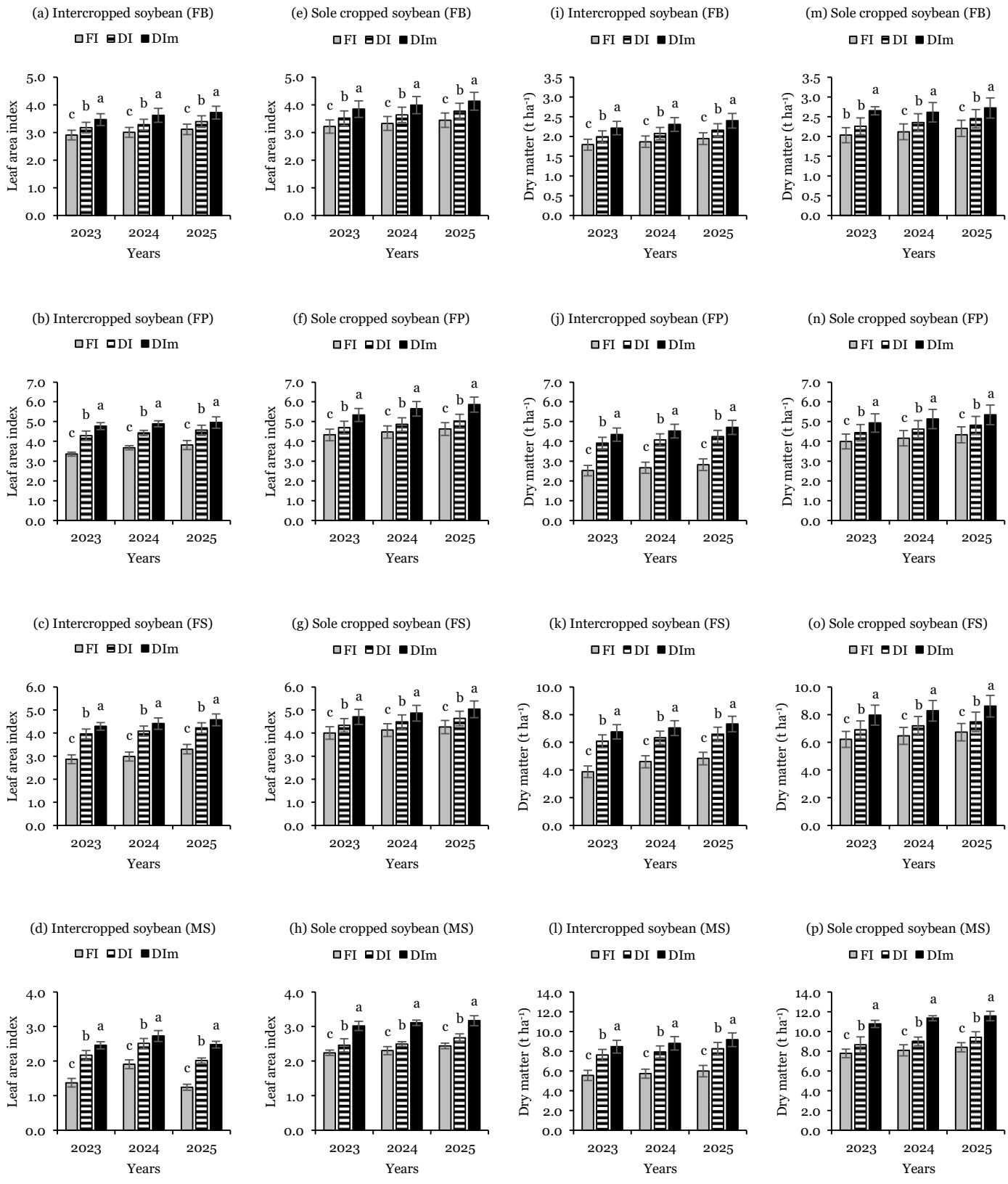


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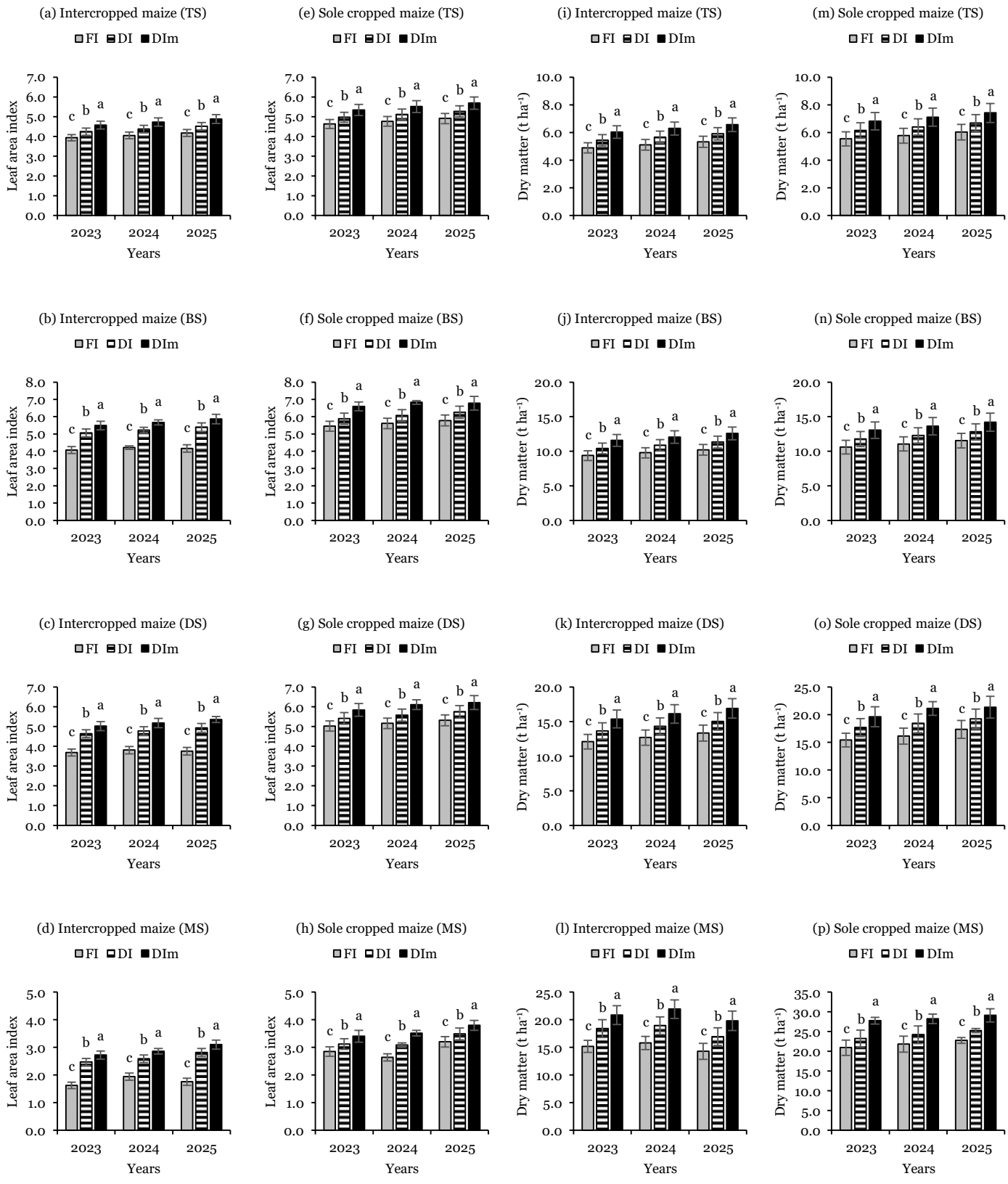


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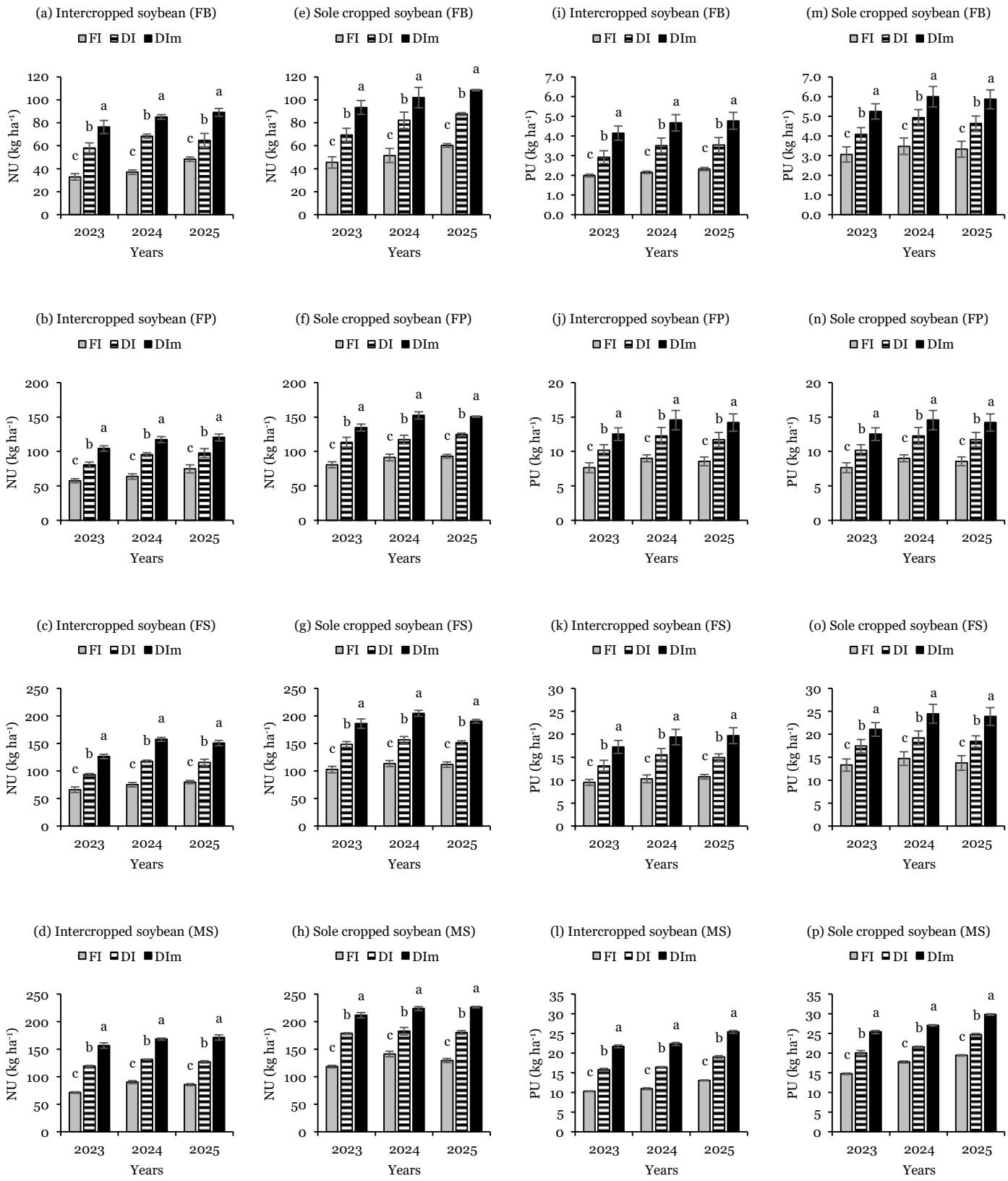


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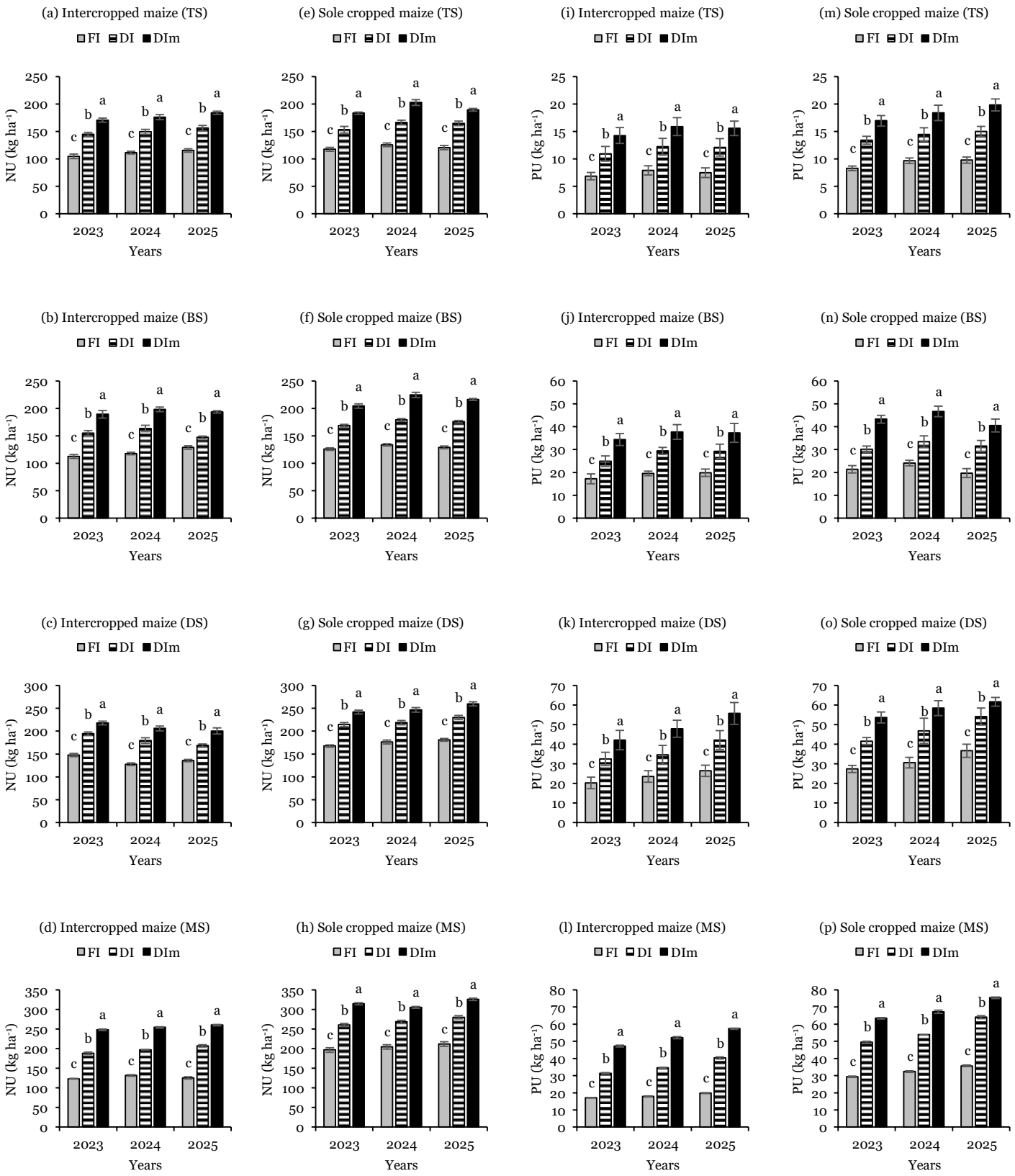


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Supplementary Files

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- OnlineResourceS1.docx
- OnlineResourceS10.docx
- OnlineResourceS11.docx
- OnlineResourceS12.docx
- OnlineResourceS13.docx
- OnlineResourceS14.docx
- OnlineResourceS2.docx
- OnlineResourceS3.docx
- OnlineResourceS4.docx
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- OnlineResourceS8.docx
- OnlineResourceS9.docx