OPTIMIZING LAND-USE EFFICIENCY IN RICE-SOYBEAN SYSTEMS THROUGH TEMPORAL OFFSETS AND SPATIAL ARRANGEMENTS OF RICE/SOYBEAN INTERCROP IN RAINFOREST AGROECOLOGY OF NIGERIA

Adewale O. Adetayo
Department of Water Resources Management and Agrometeorology
Federal University Oye-Ekiti, Nigeria
wale_agromet@yahoo.com

Abstract

Sustainable intensification of cereal-legume systems requires a precise balance between interspecific competition and facilitation. This study investigated the impact of temporal niche differentiation and spatial arrangement on the productivity of rice and soybean intercropping. A 16-treatment factorial experiment evaluated seven planting offsets (from 30 days before to 30 days after) and two row geometries (alternate vs. double). Competition was quantified using the Land Equivalent Ratio (LER), Actual Yield Loss (AYL), and Aggressivity (AA), while physiological trade-offs were modeled via regression of soybean nodulation against rice yield. Among the intercropping treatments, simultaneous planting achieved the highest rice grain yield (4.55 t/ha), representing only a 7.3% reduction compared to the sole rice control (4.91 t/ha). Delaying rice planting by 30 days optimized the system's land-use efficiency (LER = 8.49) and resulted in a significant actual yield gain (AYL = 14.98), indicating a substantial advantage over monoculture**.** A significant inverse correlation was identified between soybean nodulation and rice grain yield ($r = -0.947$, $p < 0.001$). All intercropping treatments exhibited a profound facilitation effect, rescuing the soybean component from the near-total failure observed in its monoculture (0.11 t/ha). Alternate row spacing was found to be superior for rice panicle development across all temporal offsets. It is recommended that farmers seeking maximum land-use efficiency and monetary returns, plant rice 30 days after soybean in alternate rows. This research provides a mechanistic framework for utilizing temporal offsets to enhance the resilience and profitability of legume-based intercropping systems.

Keywords: Land equivalent ratio, facilitation, temporal niche, competition indices, sustainable intensification.

Introduction

Climate-smart agriculture is an approach for developing agricultural strategies to secure sustainable food security under climate change. This approach aims to strengthen livelihoods and food security, especially of smallholders, by improving the management and use of natural resources in a sustainable manner. Global agricultural systems are currently facing a dual challenge: the need to increase food production for a growing population and the urgent requirement to reduce the environmental footprint of monoculture farming (Raza *et al*., 2023). In many regions where land availability is reaching its ceiling, sustainable intensification through intercropping has emerged as a vital strategy for enhancing land-use efficiency and system resilience (Du *et al*., 2023).

Cereal-legume intercropping, specifically the rice and soybean system, offers a promising pathway for sustainable intensification. This combination is biologically complementary; rice, as a C3 cereal, provides a high-calorie staple, while soybean contributes essential proteins and improves soil fertility through biological nitrogen fixation (Chen *et al*., 2022). However, the success of such systems is dictated by the management of interspecific competition. When two crops share the same space, they often compete for limited resources such as solar radiation, soil moisture, and nutrients, which can lead to a yield penalty for the less dominant species (Li *et al*., 2020).

The productivity of an intercropping system is primarily governed by two factors: temporal niche differentiation and spatial arrangement. Temporal niche differentiation involves offsetting the planting dates of the component crops to ensure that their peak resource demands do not overlap. While previous research has explored spatial configurations (alternate vs. double rows), there is a significant knowledge gap regarding the timing of rice planting relative to soybean, where one crop enhances the growth or survival of another (Li *et al*., 2020). Therefore, there is a need for adequate information on the production potentials of rice-soybean intercrops in the rainforest agroecological zone. The objective of this research was to investigate the potential of sustainable, climate-smart rice-legume intercrop systems for improved food security in the rainforest agroecology of Southwest Nigeria.

Rice is the most important food crop in the world, with 150 million hectares of cultivated area. As a consequence, the gap between regional demand and supply is met by regular imports of about 2.6 million tons per year in West Africa, at a cost of $800 million in foreign exchange (Nnadozie *et al.,* 2024)**.** In Nigeria, rice has become a staple food for rural populations as well as urban populations. To ensure food production for the growing population, domestic rice production must continue to increase.

Soybean, designated as the "miracle bean," has established its potential as an industrially vital and viable oilseed crop in many areas of the world. Soybeans contain approximately 40% protein and 20% oil on a dry matter basis (Omoigui *et al*., 2020). The oil is used primarily in edible products such as margarine and cooking oil, and industrially in products such as high-grade paints and pharmaceuticals. The soybean oil meal that remains after extraction is used almost entirely as a high-protein livestock feed, but the meal can be further refined for direct human consumption. Soybean is among the major industrial and food crops grown on every continent. The crop can be successfully grown in many states in Nigeria using low agricultural input. In this study, the competitive dynamics between rice and soybean were investigated with a view to optimizing the planting window and row geometry.

Materials and Methods

Study Area

This research **was** conducted during the early and late seasons of 2023 and 2024 at the project farm of the Institute of Agricultural Research and Training (I.A.R&T.) Ibadan, Nigeria (7°22'N; 3°30'E). The station is within the rainforest agroecological zone of Nigeria. Rainfall in the zone is humid to sub-humid tropical with distinct dry and wet seasons. The dry season runs from early November to the end of March, while the wet season is from early April to early November. There are two rainfall peaks (June and September) with a dry spell in August. Annual temperatures range between 28–36°C. Relative humidity is high throughout the year, ranging between 60–90% at 16:00 hours. Average daily sunshine hours range from 14 hours in August to 7.5 hours in January.

The soil varies from sandy loam at the topsoil to sandy clay loam in the subsoil. The pH of the soil ranges from 4.90 in the subsoil to 5.19 in the topsoil. Organic carbon content ranges from 1.20 g kg^{-1} in the subsoil to 13.72 g kg^{-1} at the surface. Nitrogen ranges from 0.62 g kg^{-1} to 1.28 g kg^{-1}. Available phosphorus was 8.56 mg kg^{-1} at the surface and decreased down the profile to 1.09 mg kg^{-1} in the subsoil. Calcium ranged from 0.80 cmol kg^{-1} to 1.50 cmol kg^{-1}, while magnesium ranged from 0.90 cmol kg^{-1} to 1.0 cmol kg^{-1}. Sodium ranged from 1.02 cmol kg^{-1} to 2.32 cmol kg^{-1}, and exchangeable potassium ranged from 0.08 cmol kg^{-1} to 0.14 cmol kg^{-1}.

Experimental Layout

The experiment was laid out in a Factorial Randomized Complete Block Design (RCBD) with three replicates. The factors under study were (i) two spatial arrangements: rice in alternate rows with soybean and double rows of soybean between double rows of rice and (ii) seven relative planting times of planting the component crop: planting of rice 30, 20 and10 days after soybean, sole rice, sole rice planting and planting rice, 30, 20, 10 days before soybean (Table 1).

Table 1: Treatment Combinations and Days of Planting.

Treatment code	Description
T_1S_1	Rice planted same day with soybean, soybean in alternate rows
T_1S_2	Rice planted same day with soybean, soybean in double rows
T_2S_1	Rice planted 10 days before soybean, soybean in alternate rows
T_2S_2	Rice planted 10 days before soybean, soybean in double rows
T_3S_1	Rice planted 20 days before soybean, soybean in alternate rows
T_3S_2	Rice planted 20 days before soybean, soybean in double rows
T_4S_1	Rice planted 30 days before soybean, soybean in alternate rows
T_4S_2	Rice planted 30 days before soybean, soybean in double rows
T_5S_1	Rice planted 10 days after soybean, soybean in alternate rows
T_5S_2	Rice planted 10days after soybean, soybean in double rows
T_6S_1	Rice planted 20 days after soybean, soybean in alternate rows
T_6S_2	Rice planted 20 days after soybean, soybean in double rows
T_7S_1	Rice planted 30 days after soybean, soybean in alternate rows
T_7S_2	Rice planted 30 days after soybean, soybean in double rows
Sole rice	Sole rice
Sole soybean	Sole soybean

Agronomic Practice and Data Collection

The variety of rice used is FARO 72 while the variety of soybean used is TGX 2029-53F. Three seeds per hole were planted and later thinned to two per stand at one week after planting. Weeding was carried out manually using hoe at two weeks after planting and at two weeks interval. The first planting date is at onset of rainfall. The growth and yield data include number of leaves, plant height, leaf area pods per plant, seeds per pod and yield per hectare of rice and soybean. Crop growth data were collected weekly starting from a week after planting and subsequently at one week interval.

Calculation of Competition and Economic Indices

To evaluate system productivity and interspecific competition, the following indices were calculated:

1. Land Equivalent Ratio (LER) = (Yir/Ysr) +(Yis/Ys) LER=(Yir/Ysr) +(Yis/Ys)
   where Yi is intercrop yield and Ys sole crop yield for rice (r) and soybean (s).
2. Aggressivity (AR) = (Yir/(Ysr×Zrs)) −(Yis/(Yss×Zsr)
   where, Z represents the sown proportion (0.5).
3. Competitive Ratio (CR) = (LERr/LERs) ×(Zsr/Zrs)

4. Actual Yield Loss (AYL) = AYLr+AYL
   where, AYLr = [(Yir/Zrs)/Ysr] −
5. Monetary Advantage Index (MAI) = **(**Value of Combined Yield) ×[(LER−1)/LER]

Statistical Analysis

Data were analyzed using Python (version 3.12) utilizing the pandas, stats models, and scipy libraries. A Factorial ANOVA was performed to determine the main effects of planting time and spatial arrangement. Due to the high correlation between growth parameters and final yield, a Pearson Correlation Analysis and Ordinary Least Squares (OLS) Regression were conducted to model the trade-off between soybean nodulation and rice productivity.

Results

Rice Growth and Yield Components

Table 2 shows the growth and yield characteristics of rice. The table revealed that rice grain yield followed a clear downward trend as its planting date was delayed relative to soybean. The highest grain yield was recorded in treatment T1S1(4.55 t/ha), which represented a minor reduction compared to the sole rice control (4.91 t/ha). In contrast, delaying rice planting by 30 days (T7) resulted in the lowest productivity, with yields falling to 1.42 t/ha in the double-row (S2) configuration. The number of panicles per plant decreased from a maximum of 5.2 (T1S1) to 2.8 (T5S2), before stabilizing around 3.0 in T7 treatments. Spatial arrangement S1 (alternate rows) consistently outperformed S2(double rows) across all planting dates, maintaining higher panicle lengths and spikelet counts. Despite the variation in final yield, the vegetative growth slope remained relatively stable across treatments, ranging from 1.07 to 1.30 cm/day.

Table 2: Growth and Yield Characteristics of Rice

Treatment	Height 10 DAP (cm)	Height 30 DAP (cm)	Height 50 DAP (cm)	Panicle Length (cm)	Spikelets per Panicle	Panicles per Plant	Yield (t/ha)
T1S1	11.0	25.0	58.0	25.0	145	5.2	**4.55**
T1S2	10.5	24.0	57.0	25.0	146	4.8	4.15
T2S1	11.0	25.0	60.0	24.0	138	4.8	3.96
T2S2	10.0	26.0	61.0	24.0	135	4.2	3.74
T3S1	11.0	25.0	60.0	23.0	127	4.0	3.55
T3S2	11.0	26.0	63.0	23.0	126	3.8	3.46
T4S1	11.0	25.0	59.7	22.0	125	3.7	3.27
T4S2	10.5	24.0	56.0	21.0	120	3.3	3.01
T5S1	11.0	24.0	57.8	20.0	119	3.1	3.00
T5S2	10.5	23.0	57.0	21.0	115	2.8	2.87
T6S1	10.5	23.5	56.0	20.0	116	3.0	2.46
T6S2	11.0	22.0	55.4	19.0	113	2.9	1.94
T7S1	10.5	22.0	54.5	19.0	109	3.1	1.52
T7S2	11.0	20.5	54.0	18.0	103	3.0	1.42
Sole Rice	11.5	26.0	70.5	26.0	150	7.8	**4.91**

Soybean Growth and Yield Characteristics

Soybean productivity showed an inverse relationship with rice planting time (Table 3). As rice planting was delayed, soybean yield increased from 0.60 t/ha (T1) to a maximum of 0.90 t/ha (T7. A progressive increase in biological nitrogen fixation potential the number of nodules per plant rose from 11 in T1 to 19 in T7S2. All intercropped soybean yields significantly exceeded the sole soybean control (0.11 t/ha). Leaf area and the number of pods per plant followed a similar trajectory, with T7 treatments exhibiting the highest vegetative and reproductive vigor for the soybean component.

Table 3: Growth and Yield Characteristics of Soybean

Treatment	Leaf Area (cm²)	Nodules per Plant	Pods per Plant	100-Seed Weight (g)	Yield (t/ha)
T1S1	52.4	11	44.2	14.2	0.60
T1S2	51.8	11	44.0	14.8	0.60
T2S1	56.8	11	46.9	14.9	0.70
T2S2	56.7	11	48.4	16.8	0.60
T3S1	56.7	12	52.8	16.8	0.50
T3S2	56.2	13	54.8	19.8	0.60
T4S1	66.4	13	54.8	19.9	0.70
T4S2	68.2	13	58.2	19.0	0.60
T5S1	72.4	13	58.8	19.0	0.70
T5S2	72.0	15	60.4	19.2	0.80
T6S1	76.1	18	60.2	18.4	0.60
T6S2	75.0	18	60.2	18.6	0.60
T7S1	78.4	18	64.8	22.8	**0.90**
T7S2	77.2	19	65.4	22.9	**0.90**
Sole Soy	80.3	23	77.1	23.4	0.11

System Productivity and Competition Indices

System productivity, measured via the Land Equivalent Ratio (LER), indicated a significant biological advantage for all intercropping combinations (LER > 1.0) (Table 4). The total LER ranged from 5.27 (T3S1) to a peak of 8.49 (T7S1). The high LER in the T7 treatments was driven by the high partial LER of soybean. Actual Yield Loss (AYL) analysis confirmed these findings, with Total AYL reaching its maximum at 14.98 in T7S1. In this context, a positive AYL signifies a yield gain per plant compared to monocultures, indicating that the intercrop environment facilitated better individual plant performance than the stressed sole-crop control. Aggressivity indices for rice (Ar) were consistently negative across all treatments, confirming that rice was the subordinate species in the mixture, while soybean acted as the dominant competitor, particularly in delayed planting scenarios. The Monetary Advantage Index (MAI) followed the productivity trends of the LER. The highest economic returns were generated by the T7S1 treatment, which maximized the total system value despite the lower rice yield. Despite the low rice yields in later treatments, the Monetary Advantage Index (MAI) was highest in T7S1 (3,952). This proves that the high yield of soybean and the total system efficiency (LER) carry more financial weight than the rice yield alone. The alternate row spacing (S1) yielded higher MAI values than the double-row (S2) arrangement within the same planting date factor.

Table 4: System Productivity, Competition Indices, and Economic Returns

Treatment	Leaf Area (cm²)	Nodules per Plant	Pods per Plant	100-Seed Weight (g)	Yield (t/ha)
T1S1	52.4	11	44.2	14.2	0.60
T1S2	51.8	11	44.0	14.8	0.60
T2S1	56.8	11	46.9	14.9	0.70
T2S2	56.7	11	48.4	16.8	0.60
T3S1	56.7	12	52.8	16.8	0.50
T3S2	56.2	13	54.8	19.8	0.60
T4S1	66.4	13	54.8	19.9	0.70
T4S2	68.2	13	58.2	19.0	0.60
T5S1	72.4	13	58.8	19.0	0.70
T5S2	72.0	15	60.4	19.2	0.80
T6S1	76.1	18	60.2	18.4	0.60
T6S2	75.0	18	60.2	18.6	0.60
T7S1	78.4	18	64.8	22.8	**0.90**
T7S2	77.2	19	65.4	22.9	**0.90**
Sole Soy	80.3	23	77.1	23.4	0.11

Figure 1 shows the system performance and biological drivers of the rice-soybean intercropping system. Heatmap of Land Equivalent Ratio (LER) optimization across seven planting time factors and two spatial arrangements (1 = alternate rows, 2 = double rows). Higher LER values (darker blue) indicate superior land-use efficiency. Regression analysis of the biological trade-off between soybean nodulation and rice grain productivity. The integrated performance (as summarized in the Heatmap, Fig 1a) confirms that while rice yield is maximized under simultaneous planting, the total system efficiency and biological stability are optimized when rice planting is delayed by 30 days. The strong inverse correlation ($r=-0.95$) and shaded area (95% confidence interval) highlight the competitive displacement of rice as soybean nitrogen-fixation potential increases. The interplay between management factors and output was further elucidated through heat-mapping and regression modeling (Figure 1). The LER Optimization Map (Fig.1b) identified a distinct Maximum Efficiency Zone at 30-day delay in rice planting, where system efficiency peaked regardless of row spacing (LER=8.49LER=8.49 and 8.47). While alternate rows were superior at earlier planting stages (T2 and T4), the system reached a saturation point by T7 where spatial geometry became a secondary driver to temporal niche differentiation.

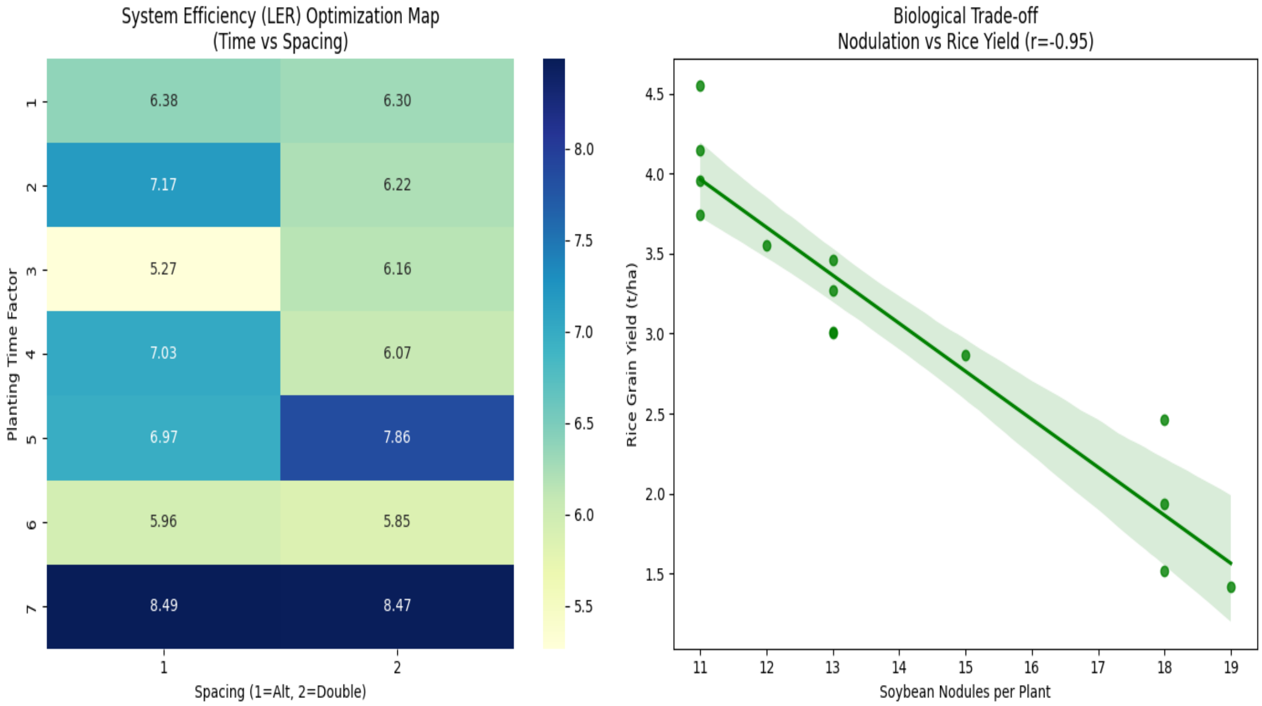

Figure 1a and b**:** System performance and biological drivers of the rice-soybean intercropping system: (a) Heatmap of Land Equivalent Ratio (LER) optimization across planting times and spatial arrangements; (b) Regression analysis showing the inverse relationship between soybean nodulation and rice grain yield (r = -0.95).

Discussion

The strong negative correlation between soybean nodulation and rice grain yield suggests a classic case of temporal niche differentiation and resource pre-emption. As rice planting was delayed, the soybean component established a head start, allowing it to develop a robust root system and leaf canopy before the rice entered its critical vegetative phase. This aligns with the findings of Li *et al.* (2020), who reported that staggered planting dates in relay intercropping reduce the competitive overlap for light and nutrients. The 30-day delay in rice planting allowed soybean to reach its peak nodulation and biomass expansion phase without competition from the rice seedlings. However, this head start created a competitive asymmetry where the dominant soybean component likely pre-empted soil moisture and light interception, leading to the observed reduction in rice yield.

The reduction in rice yield was primarily driven by a decline in the number of panicles per plant and spikelet counts, rather than a failure of vegetative growth. The growth slope analysis showed that rice maintained a consistent height increase across treatments, suggesting that the competition exerted by soybean was not lethal but instead limited the reproductive sink capacity of the rice. This confirms the theory of Yu *et al*. (2021), who noted that in cereal-legume systems, the subordinate cereal crop often exhibits phenotypic plasticity, prioritizing survival and vegetative height over reproductive output. Furthermore, the superiority of alternate row spacing over double rows suggests that spatial arrangement plays a critical role in mitigating shading effects. Alternate rows likely provided a more uniform light distribution to the rice canopy, a mechanism supported by Wang *et al.* (2023), who found that spatial geometry is as critical as temporal timing in managing interspecific light competition.

The high Land Equivalent Ratio (LER) of 8.49 observed in the T7S1 treatment is a reflection of the near-total failure of the soybean monoculture (0.11 t/ha) compared to its performance in the intercrop system (0.90 t/ha). This suggests an obligatory facilitation effect in the agroecology. While the sole soybean likely succumbed to site-specific environmental stressors, such as high soil surface temperatures or pest pressure, the presence of rice in the intercrop treatments likely provided a modified microclimate and nitrogen-sparing environment that rescued the soybean component. Consequently, the system efficiency is driven not just by yield addition, but by the intercrop's ability to provide biological insurance against monoculture failure.

There was a high Land Equivalent Ratio (LER) and Actual Yield Loss (AYL) indices, particularly in the 30 days delayed in rice planting treatments. These values were driven by the facilitation bonus observed in the soybean component, which yielded up to 800% more than the sole soybean control. This suggests that the intercropping environment provided a facilitation effect that was absent in the monoculture. As Du *et al*. (2023) and Guan *et al*. (2023) argued, the presence of a companion crop can improve the microclimate, reduce soil evaporation, and suppress pests. Soybean nodulation increasing significantly in the intercropped plots suggests that the presence of rice may have stimulated soybean BNF activity through a nitrogen-sparing mechanism, where the rice crop consumed soil nitrogen, forcing the soybean to rely more heavily on atmospheric fixation (Chae and Anderson, 2021; Maitra *et al*, 2021). The low productivity of the sole soybean crop suggests that it may have been exposed to site-specific environmental stresses that were mitigated by the intercropped rice.

While rice-focused farmers might view the yield reduction in as a failure, the Monetary Advantage Index (MAI) results tell a different story. The highest system profitability achieved in delayed rice planting highlights the trade-off inherent in sustainable intensification, maximizing the productivity of a single staple crop versus maximizing the total system value. In regions where land is scarce, the high LER and MAI of the delayed planting system suggest it is a superior strategy for total food production and income stability (Guan *et al*., 2023). This approach aligns with the global mandate for sustainable intensification, as described by Yu *et al.* (2021) and Raza *et al*. (2023) by producing more total calories and protein per unit area than monocultures, while utilizing the biological advantages of legume-based nitrogen fixation.

Conclusion

This study demonstrates that the productivity and competitive dynamics of rice-soybean intercropping are primarily governed by temporal niche differentiation rather than spatial arrangement alone. The results suggest that the competitive balance between the cereal and legume components is more sensitive to temporal niche differentiation than to spatial row arrangement. Sacrificing the yield of the primary staple (rice) proved to be a scientifically sound strategy to achieve higher total system stability and protein output, providing biological insurance against monoculture failure. The increased nitrogen-fixing potential and vegetative vigor of soybean in the delayed rice planting created a dominant competitive environment that limited rice reproductive sink capacity. Configuration is particularly relevant for smallholder farmers in land-constrained regions, as it provides a robust biological insurance against monoculture failure and maximizes total caloric and economic output per unit area.

This research bridges the gap between ecological theory and practical agronomy, proving that sacrificing the yield of a primary staple can be a scientifically and economically sound strategy to achieve higher total system stability and protein output. Agricultural development programs should transition from supporting monocultures to incentivizing legume-based intercropping to improve national protein security and reduce the demand for synthetic nitrogen. Future efforts should focus on integrating these temporal strategies with climate-smart irrigation and site-specific nutrient management to further enhance the resilience of legume-based intercropping systems in the face of global environmental change.

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