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Optimizing Upland Rice–soybean Intercropping for Enhanced Productivity, Resource Use Efficiency, and Farmer Income

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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

MAK 4 soybean, a widely grown and early maturing variety, offers potential compatibility with upland rice due to its growth habit and soil fertility benefits. The study aims to assess the growth and yield performance of different upland rice varieties when intercropped with MAK 4 soybean. A field experiment was conducted during the first and second rainy seasons of 2024 and 2025 at the Buginyanya Zonal Agricultural Research and Development Institute, Ikulwe satellite station in Eastern Uganda. The experiment was laid out in a randomized complete block design with three replications, consisting of eleven treatments combining five rice varieties (NERICA 1, NERICA 4, NERICA 10, NamChe 3, and NamChe 5) grown as sole crops and

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intercropped with soybean (MAK4), alongside a sole soybean control. Plant height and leaf length of intercropped rice were significantly (P≤0.05) greater than those of sole crops, except for NERICA 1 + soybeans. Plant height and leaf length of intercropped rice were significantly (P=0.05) greater than sole crops except for NERICA 1 + soybean. Rice leaf length increased notably in 2024 due to soybean introduction, except for NERICA 10. Intercropping did not affect MAK4 soybean height, pods per plant or grain yield significantly (P=0.05), over the two years, but reduced soybean pods by 0.08-30% while increasing rice height (0.004-12%) in 2024. Tiller and panicle numbers were unaffected in both years. The combined land equivalent ratio of rice + soybean was 1.75 & 1.68 for NamChe 3 and 1.87 & 1.75 for NamChe 5 + MAK 4 soybean, indicating high land use efficiency. High LEC and REY values occurred with Soybean + NamChe 3 and Soybean + NamChe 5, while low ATER values were observed for the same treatments. TRGYE scores were higher under intercropping than sole rice in both years, with the highest values in 2025. The competition ratio was significantly high (<0.001) under NERICA 1 + soybean (1.98 & 1.34) and low under NamChe 5 (0.83 & 0.85) and NamChe 3 (1.27 & 1.26). The study concludes that NamChe 3 + MAK 4 soybean and NamChe 5 + MAK 4 soybean are sustainable intercropping systems for maximizing land productivity and farmer income in upland systems.

Keywords: Agronomic performance; land equivalent ratio; MAK 4 Soybean; NamChe; yield attributes.

1. Introduction

Rice (*Oryza sativa* L.) is a staple food for more than half of the world's population (Banjara et al*.,* 2021). It is grown in over 100 countries, with 90% of the total global production from Asia (Emerick & Ronald, 2019). However, with the current global population of 8.3 billion people, which is projected to be 9.8 billion by 2050, rice breeding programs face the daunting task of meeting the escalating demand while ensuring environmental sustainability (Ishfaq et al., 2023). The adoption of improved upland rice varieties has been promoted to increase yields under rainfed conditions, but their performance when integrated into intercropping systems remains poorly documented. Upland rice has been grown as a major crop as well as a rotation crop for both generating incomes and soil improvement (Phapumma et al., 2020). Upland rice production uses less irrigation water and needs less labour. It is suitable for sloping fields that are prone to erosion, as well as drought-prone locations (Langangmeilu et al., 2023). At the same time, MAK 4 soybean, a widely grown and early maturing variety, offers potential compatibility with upland rice due to its growth habit and soil fertility benefits. Row intercropping, the practice of growing two or more crops simultaneously on the same field in distinct rows and optimizing spatial row arrangements and interactions, is being promoted (Bugilla et al*.,* 2023). The principal reasons for smallholder farmers to intercrop are weed control, balanced nutrition (Mortensen et al*.,* 2000), flexibility, risk minimization against total crop failure, soil conservation, pests/ disease management and improvement of soil fertility (Lanker et al*.,* 2020; Huang et al., 2025). The cropping system has been widely studied for its potential to enhance resource use efficiency, increase crop productivity and economic returns compared to traditional monoculture systems (Anim-jnr et al*.,* 2023) and provide ecological benefits (Brooker et al*.,* 2023). The system is especially prevalent in resource-limited agricultural systems (Brooker et al., 2015). The land equivalent ratio (LER), area time equivalent ratio (ETER), monetary advantage index (MAI), rice equivalent yield (REY), and total rice grain yield equivalent (TRGYE) serve as pivotal metrics to assess the system productivity and its economic benefits compared to conventional agricultural systems. An LER greater than 1.0 signifies that intercropping yields higher productivity on the same land area compared to monoculture practices. This highlights the efficiency and sustainability of this farming approach (Morales-Rosales & Franco-Mora, 2009).

Intercropping is a crop diversification strategy which allows lowering inputs while achieving higher crop yields than expected based on the sole crop yields of the constituent species. Due to its contribution to efficient use of resources and diversification of crop species, the system provides a compelling opportunity for the sustainable intensification of agriculture (Li et al., 2023). The conventional method of planting rice (30 x 12.5 cm hills) does not permit intercropping because of narrow row spacing and intensive binding of soil by the root mass of closely growing rice plants. In monocropping systems, crops get intraspecific competition in their location above and below the surface. Seran & Brintha (2010) reported that the seeding rate of each crop under intercropping systems must be adjusted to below its full rate to optimize plant density. If full rates of each crop were planted, neither would yield well because of intense overcrowding and competition. A new pattern of planting rice in wide-spaced paired rows, maintaining normal plant population, has, however, been developed. This additive series, where the main crop population is adopted in twin rows, maintains the plant population, creating space for a legume intercrop, relative to the replacement planting, which reduces the population of one component crop through crop substitution. The system not only gives high yield comparable to the conventional planting system, but also facilitates interplanting, management and harvesting of intercrops without damage to the rice (main) crop. Rice and soybeans are C_3 plants that use the standard C3 photosynthetic pathway (Calvin cycle) to efficiently use the enzyme Rubisco to fix carbon dioxide (CO_2) directly into a three-carbon compound (3-phosphoglycerate). The pathway does not require the complex anatomy seen in C_4 plants and works well under moderate temperatures and when there is sufficient water. C_3 plants benefit from the rising levels of atmospheric CO_2 concentrations in a phenomenon known as the CO2 fertilization effect in the context of climate change. C_3 plants can grow well, even as some of the heat effects of climate change take hold. Much as soybeans are vulnerable to challenges of high temperatures and moisture stress, it benefits from the symbiotic shading effect of the rice crop planted in the East -West orientation. Kaiira et al. (2023) recorded higher rice growth and grain yields in the East -West row orientation. Increased shading by the EW crop minimizes weed growth by reducing the soil surface temperature and evaporation in the inter-row space, leading to increased soil moisture. The increased moisture occasionally increases crop yield where moisture is limited (Mead and Willey 1980).

Soybean (*Glycine max)* and upland rice (*Oryza sativa*) are essential crops for smallholder farmers in many regions. Technologies in rice and soybeans, such as improved soil fertility and overall system productivity, are documented, but there is a need to investigate innovative methods and technological breakthroughs that provide a deeper understanding of intercropping systems, as limited research has been conducted to evaluate the specific combination of MAK4 soybean and various upland rice varieties. Some scientists (Ghaffar et al., 2022; Pierre et al., 2022; Homulle et al., 2021; Jensen et al., 2020) have attributed the higher benefits of cereal-legume intercropping systems to low fixed costs for land as a result of a second crop in the same field and efficiency in tapping solar radiation. Benefits of row intercropping have also been associated with improved resistance and defense mechanisms from diverse genotypes (Bass et al., 2024), disease management (Zhou et al., 2023), soil fertility and health (Kumar et al., 2023 & Janati et al., 2023), organic matter accumulation and carbon (Ma et al., 2022). Other scientists attributed the benefits to pollinators (Ghaffar et al., 2022), soil microbes (Ma et al., 2022 & Lai et al., 2022), resistance to changing climatic conditions (Ghaffar et al., 2022) & Stomph et al., 2020), pests control (Li et al., 2021), high water use efficiency (Jhariya et al., 2021, beneficial bacteria (Qu et al., 2020), nitrogen fixation (Yuvaraj et al., 2020) and weed control (Bibi et al., 2019). Increased nitrogen availability by particular flavonoids released by legumes, which promote nitrogen-fixing bacteria, was reported by Dong et al. (2022). Breeding efforts aimed at enhancing intercropping efficiency have begun to identify specific markers associated with these advantages. (Bourke et al., 2021). Recently, high relative equivalent yield and monetary advantage indices were recorded under rice + soybeans by Kaiira et al. (2024). Rice was observed to be more aggressive than other crops. Intercropped treatments recorded a higher Total Rice Grain Yield Equivalent (TRGYE) than sole rice. Rice + soybeans scored higher TRGYE. The LER for rice + soybean were 1.39 (2022) and 1.21 (2023).

Ozioma et al. (2024) reported that Rice 50/Soybean 50 gave the highest total land equivalent ratio (TLER), land equivalent ratio (LER), and per cent land saved. Erythrina et al. (2022) similarly reported lower costs of production under intercropping than mono-cropping practices. Yield advantage (LER) for rice-soybeans were 54% compared to mono cropping, and REY and gross margins under intercropping were significantly higher than under mono cropping. Singh et al. (2021) reported LER greater than unity under rice intercropping systems. Mugisa et al. (2020) earlier indicated that intercropping rice with beans, groundnuts and maize led to more yield benefits from the LER under an average of 1.5. The best intercrops with better yields and higher LERs were rice-beans and rice-maize mixtures. Little work has been done on rice-based intercropping systems with soybean in Uganda. Evaluating how different upland rice varieties perform when intercropped with MAK 4 soybean is, therefore, crucial in identifying combinations that optimize yield, resource use efficiency, and overall system productivity. This study was conducted with the major objective of evaluating the performance of five selected upland rice varieties intercropped with MAK 4 soybean variety under paired rows of rice in the EW with the following specific objectives: (1) To assess the growth and yield performance of different upland rice varieties when intercropped with MAK 4 soybean (2) To evaluate the rice-soybean interspecific competition using competitive indices (3) To identify the most productive and compatible rice-soybean combination for upland farming ecosystems. The findings of this study are anticipated to guide the design of more productive and sustainable rice-based cropping systems for smallholder farmers, particularly in agro-ecological settings where land scarcity and soil fertility decline limit agricultural productivity.

2. Materials and Methods

2.1 Study Site During 2024 and 2025

2.1.1 Location

The study was conducted at the Buginyanya Zonal Agricultural Research and Development Institute, Ikulwe satellite station in Mayuge District of Eastern Uganda during the second and first rain seasons of 2024 (September-December) and 2025 (March – June) respectively. Ikulwe is located at 00^0 26'23.2N 0330 28'40.9E, at 1209 meters above sea level.

2.1.2 Rainfall and Temperature

The data on rainfall during September-December 2024 and March-June 2025, as measured at Ikulwe satellite station, are indicated in Figs. 1 and 2. The monthly total rainfall during 2025 (860.0 mm) was higher than during 2024 (730.0 mm). During 2024, the mean cropping season's minimum and maximum temperatures were 19.2 °C and 30.5°C against the annual average temperatures of 18.3°C and 32°C, respectively. The mean minimum and maximum temperatures during the 2025 cropping season were 18.6°C and 31.8°C, respectively.

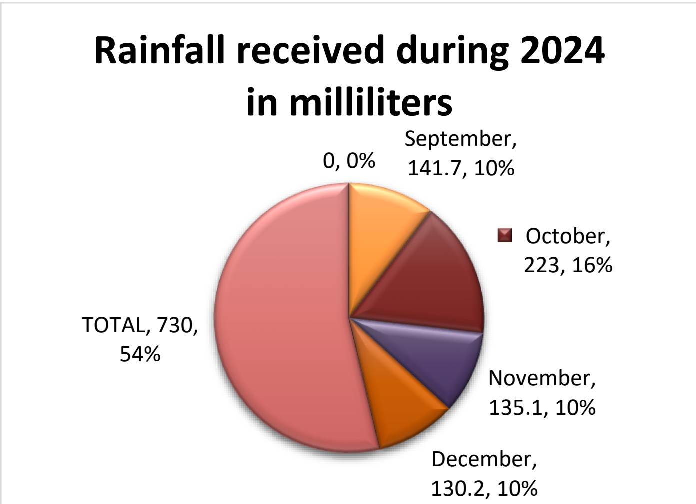

Fig. 1. Rainfall received during 2024

2.1.3 Soil Properties

The physico-chemical properties of the Luvisol were analyzed before the experiment. The soil had a mean pH of 5.7 and a texture comprising 54% sand, 23% silt, and 23% clay. Soil organic matter content was 3.6%, with available nitrogen at 0.19%, and exchangeable phosphorus and potassium concentrations of 5.08 mg kg^{-1} and 5.09 mg kg^{-1}, respectively. These analyses were conducted to determine the nutrient deficiencies and to inform appropriate fertilizer application rates.

2.2 Experimental Design and Treatments

The experimental design was a randomized complete block design with three replications. Plot sizes of 5m x 5m were maintained throughout with a 1m strip between plots. The studies were conducted for two growing seasons, from September to December in 2024 and March to June in 2025, with 11 treatments each year, namely: T_1 = Paired row sole NERICA 1 rice. T_2= Paired row sole NERICA 4, T_3= Paired row sole NERICA 10 rice, T_4= Paired row sole Namche 3 rice, T_5= Paired row sole Namche 5 rice, T_6 = Paired row NERICA 1 rice + 1 row of soybean, T_7 = Paired row NERICA 4 rice + 1 row of soybean, T_8 = Paired row NERICA 10 rice + 1 row of soybean, T_9 = Paired row Namche 3 rice + 1 row of soybean, T_{10} = Paired row Namche 5 rice + 1 row of soybean. The MAK4 soybean variety was used, and one conventional control treatment for MAK4 soybean

(T_{11}) was also included. The rice seed was directly planted in EW orientation using the drilling method in all treatments. Conventional sole soybean was planted at 50 x 12.5 cm, and the intercrop was established at 40/20x 12.5 cm in paired rows with one seed per hill in all treatments. The rice main crop and legume intercrops were planted at the same time. Fertilizers were applied to the rice crop at a rate of 100 kg ha^{-1}, 60 kg ha^{-1} and 40 kg ha^{-1} of NPK in the form of Urea, Triple Super Phosphate (TSP) and Muriate of Potash (MOP), respectively. The entire TSP and MOP were applied as basal at planting, while Urea was top dressed in three equal splits at 15 days after emergence (DAE) of rice, 30 DAE (tillering stage) & 45 DAE (panicle initiation stage) to the rice crop only. No fertilizers were applied to the legume crops. One application of Dudu force (Abamectin (20g/L) + Acetamiprid (3%) at 50ml in 20 liters of water was applied to all the crops at 45 DAE.

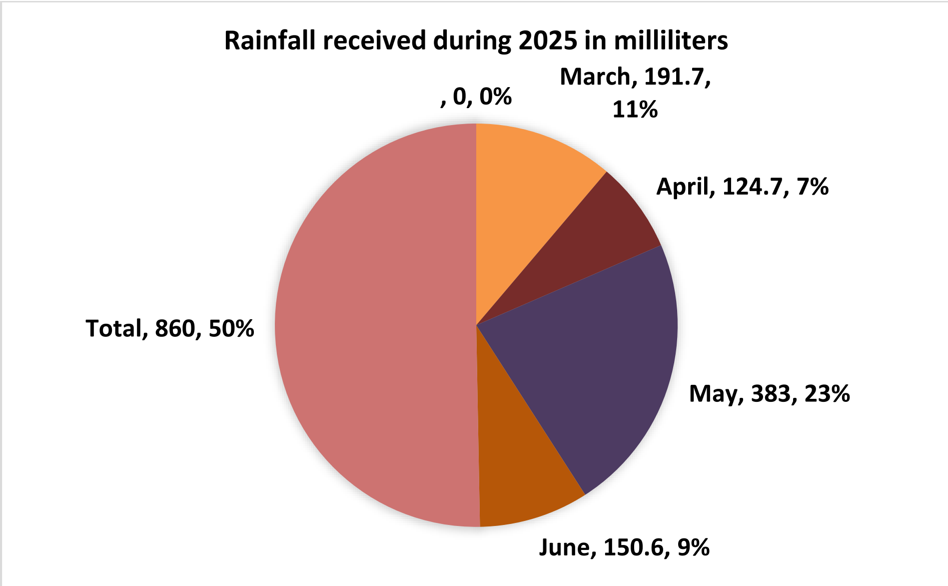

Fig. 2. Rainfall received during 2025

2.3 Data Collection and Analysis

2.3.1 Biometric Data

Ten rice plants were selected and tagged for biometric data measurements at 21 DAE on plant height, number of tillers and leaves, leaf length and width. At the panicle initiation stage (45 DAE), plant height was taken from the base of the plant to the base of the flag leaf and the longest and widest parts of the leaves were taken on the tagged plants. Before harvest, 20 plants per plot were selected randomly (excluding border hills) for the collection of data on yield parameters that included panicles per plant and grains per panicle, 1000 grain weight for rice, besides pods per plant and plant height for the legumes. The maturity period for rice differed and at harvest of (NERICA 1 & 10 (90 days), intercrops of soybean and other rice (100 DAE) and sole soybean (105 days) within the net plot (45 m^2) were harvested, dried on a cemented floor and the panicles and pods were carefully threshed/ opened, seeds were cleaned and further dried in the Agronomy Field Laboratory to record the data on grain yield. Yield was obtained by extrapolating to t ha^{-1}.

2.3.2 Competitive Indices

2.3.2.1 Land Equivalent Ration (LER)

The LER, defined as the relative land area required as a sole crop to produce the same yields as intercrops, was calculated using the formula: $LER = \sum (Yp_i/Ym_i)$.

Where Y_p is the yield of each crop or variety in the intercrop or polyculture, and Ym is the yield of each crop or variety in the single crop or monoculture.

LER indicates the efficiency of intercropping, using the environmental resources compared to monocropping (Khanal et al. 2021). When LER > 1, the intercropping favors the growth and yield of the species. In contrast, when LER < 1, there is no intercropping advantage.

2.3.2.2 The Area Time Equivalent Ratio

The Area Time Equivalent Ratio (ATER) shows the yield + time advantage and was calculated using the following formula:

ATER= (LERa /LERb) x (DC/ Dt), based on the duration to harvest for rice (90-100 days), and sole soybean (105 days) and intercropped soybeans (100 days); where LERa is land equivalent ratio of base crop, LERb is land equivalent ratio of the intercrop, DC is duration (days) taken by base crop and Dt is days from planting to harvest for the intercrop. Area time equivalent ratio (ATER) provides a more realistic comparison of the yield advantage of intercropping over monocropping in terms of time taken by component crops in the intercropping systems (Yahuza 2011).

2.3.2.3 Land Equivalent Coefficient

The land equivalent coefficient (LEC) shows the intercropping advantage and is calculated by the formula:

LEC = LERa x LERb

If LEC is greater than 0.25, then it is advantageous for the 2 crops as intercrops.

2.3.2.4 Land Use Efficiency

Since the LER value is often overestimated and the ATER value underestimated, they were averaged to provide a more accurate estimate of land use efficiency (LUE). By utilizing LER plus ATER, the LUE percentage was determined (*Mason* et al*.,* 1986) using the formula:

LUE = LER + ATER/2 x 100

2.3.2.5 Partial Yield difference

Partial Yield Difference (PYD) is defined as the yield difference between the sole crop at full population and the intercrop, expressed as a percentage. The PYD between the monoculture and the intercropping was calculated (Afe & Atanda, 2015) using the formula:

PYD = Yi -Ys

Where Yi and Ys are the yields as intercrops and sole crops (t/ha) respectively.

2.3.2.6 Rice Equivalent Yield

The rice equivalent yield (REY) for 2024 and 2025 was calculated in Kg ha^{-1}, based on the current market price in Uganda Shillings (UGX) of P_r (Rice): 3500 and P_x (Soybeans):3,000 UGX. The REY was calculated to compare system performance by converting the yield of non-rice crops into equivalent rice yield on a price basis, using the formula: REY = Yx (Px/Pr)

Where Yx is the yield of non-rice crop (kg Ha-1), Px is the market price of non-rice crops at harvest.

2.3.2.7 Total Rice Grain Yield Equivalent

The total rice grain yield equivalent (TRGYE) was calculated for the different intercropping systems by summing the yield on intercropped rice and the REY under intercropping using the formula: TRGYE = Yr + REYx.

Where Yx is the yield of rice and REYx is the rice equivalent yield for the intercrop with rice.

2.3.2.8 Competitive Ratio / Competitive Index (CI)

This was used to assess the competitive ability of the component crops in an intercropping system. The competitive ratio (CR) represents the ratio of the individual LERs of the two component crops (Khanal et al. 2021; Weigelt and Jolliffe 2003). The Competitive ratio is calculated by the formula;

Crop A: CRa = LERa/LERb   Crop b: CRb = LERb/LERa

Where LERa and LERb are the land Equivalent Ratios of crops a and b.

Where CRa = the competitive ratio of the main crop (rice), CRb = the competitive ratio of the associate crop in the intercrop

The competitive Index (CI) is calculated using the formula: CIa = LERa/LERb x Zb/Za, and CIb = LERb/LERa X Za/Zb.

Where: Za and Zb are proportions of crops A and B in the mixture.

When CRa >1, there is a positive benefit of intercropping, suggesting that the main crop can be grown in association with the associated crop, whereas when CRb>1, this is an indication of a negative benefit. If the difference between CRa and CRb is 0, then the main crop and companion crop are equally competitive. If subtracting CRb from CRa (CRa – CRb) gives a positive value, then crop A dominates crop b and exerts a stronger competitive pressure (for light, nutrients, space, etc.) than crop b (Raza et al*.,* 2020).

2.3.2.9 Aggressivity

Aggressivity value (A) is an index that determines the competitive ability of a crop when grown in association with another crop. It measures how much the relative yield of one crop component is greater than that of another (Machiani et al., 2018). An aggressivity value of zero indicates that component crops are equally competitive.

Aggressivity (A) is expressed as LERa x Pbi or LERb x Pbi.

Where: Pbi is the proportion of the base crop in the mixture with intercrop, and Pi is the proportion of the intercrop in the mixture. If Ab or Ai = 0, both crops are equally competitive. When Ab is positive, then the base crop species is dominant, and when it is negative, then the intercrop is the dominating species. It may thus be put as:

$$Aab = \frac{(Ya\ int)}{(Ya sol \times Za)} \quad \frac{(Yb\ int)}{(Yb sol \times Zb)}$$

Where: Ya*int* is the yield of the base crop (rice) under intercropping, Ya*sol* is the yield of the sole rice, and Z*a* is the sown proportion of rice in the mixture. Y*bsol* is the yield of the legume (soybean) intercrop, Y*bsol* is the yield of the sole intercrop, and Z*b* is the sown proportion of the legume intercrop.

2.3.2.10 Economic Efficiency Assessment

We performed an economic analysis to determine each intercrop's financial viability. Production facilities are all items purchased for field production, such as seeds, fertilizers, and pesticides. Contractual costs include land preparation, planting and harvesting labour costs. The variable costs denote the total expenses on production, including field purchases, plus the cost for workers in each system and inputs. The cost of production is the total that a farmer spends on cultivating one acre per planting season. We calculated the total expenses for the production based on local rates. Revenues were calculated by multiplying the grain yield of upland rice or soybeans by the farm gate prices in 2024 and 2025. The gross margin was determined by subtracting the revenues from the total variable costs for each year. The revenue cost ratio was calculated by dividing the revenues by the total production cost.

The yields of all crops in different intercropping systems and sole cropping systems, along with their economic returns, were analyzed using the income equivalent ratio (IER), monetary advantage index (MAI) and the income equivalent ratio (IER).

Monetary advantage index (MAI) was calculated using the formula:

$$MAI = \frac{\text{(Value of intercrop)}}{LER} \times (LER-1)$$

If MAI is positive, then the intercrop is profitable. The monetary advantage index (MAI) is an important index for determining the economic viability of intercropping and was determined as described by Soniya et al. *(*2021): MAI = value of combined intercrops × (LER−1) / LER. The higher the index value, the more profitable the cropping system (Dhima et al*.,* 2007).

The income equivalent ratio (IER) is the relative land area required under a sole crop to acquire the equivalent gross income as received from one hectare of intercropping at the same management level. It comprises the conversion of LER in terms of economic returns. IER > 1 denotes that the intercropping system is advantageous. The formulae for IER given (Soratto et al*.,* 2022) are as follows;

$$IER = GIia/GIsa + GIib/GIsb$$

$$IER = \frac{(GIia + GIib)}{(GIsa + GIsb)}$$

Where: GIia and GIib are the individual gross incomes for intercropping, and GIsa and GIsb are their gross incomes as sole crops, respectively.

The Income Equivalent Ratio (IER) shows whether intercropping provides higher total income than growing the component crops separately.

$$IER = IERa + IERb$$

Where: $IERa = \frac{\text{Income of crop a in intercrop}}{\text{Income of crop b in a sole crop}}$

Income for each crop is calculated as;

Income = Yield x Price. If the IER>1, then there is an advantage under intercropping. IER is more relevant than LER because it uses yield differences, market prices and economic benefits.

2.3.2.11 Data Analysis

We compared treatment means in the statistical analysis (Gomez & Gomez, 1984). The least significant difference (LSD) at a 5% level was applied using the GenStat statistical package, one-way Analysis of Variance (ANOVA) to examine the significance of differences in all data for intercropping and mono-cropping systems.

3. Results

3.1 Plant Height, Leaf Length, Leaf Width and Number of Tillers Per Plant for Rice during 2024 and 2025

The data on plant height, leaf length, leaf width and number of tillers per plant for 2024 and 2025 are indicated in Table 2. During 2024, the plant height and leaf length significantly ($P \leq 0.05$) differed among the treatments. NERICA 4 intercrop (77 cm), NERICA 10 intercrop (78 cm), NamChe 3 intercrop (83 cm) and NamChe 5 intercrop (76 cm) recorded significantly ($P \leq 0.05$) taller rice plants. This was similar to the height of sole NERICA 10 (76 cm) and sole NamChe 3 (79 cm). Sole NERICA 1, sole NERICA 4, Sole NamChe 5 and NERICA 1 + soybeans produced significantly ($P \leq 0.05$) shorter rice plants. Rice plant height was not significant during 2025. The leaf length for rice significantly ($P \leq 0.05$) increased during the 2 seasons due to the introduction of soybean intercrops, except for intercropped NERICA 10 rice that recorded significantly ($P \leq 0.05$) lower leaf length during 2024 (30 cm) and 2025 (32 cm). Significantly ($P \leq 0.05$) lower leaf length was noted for sole NERICA 1 (35 cm), sole and NERICA 10 intercrop (30-32cm) during 2024 and 2025. The leaf width and number of tillers per plant were not significant during the 2 seasons.

3.2 Plant Height and Pods per Plant and Yield for Legumes During 2024 and 2025

The data on height, pods per plant and yield for sole and intercropped soybeans during 2024 and 2025 are indicated in Table 2. Introduction of soybeans in rice did not significantly ($P \leq 0.05$) change the legume plant height, pods per plant and grain yield during the 2 years. The legume height, however, increased by 0.006-24% under different intercropping treatments, with higher legume height under Soybean intercropped in Namche 5 rice during 2024. Intercropping of soybeans, as in rice varieties, reduced the pods per plant by 0.08-30%, and the higher per cent drop (30%) in pods was recorded when Soybean was intercropped with NamChe5 rice during the year 2024. Intercropping soybean with different rice varieties increased rice height by between 0.004 12%, and reductions in pods per plant between 15 and 30% were similarly recorded during the 2025 study. During 2024, soybean grain yield declined under intercropping with NERICA 1(5%), NERICA 4 (21%), NERICA 10 (34%) and NamChe 3 (23%), but the soybean yield increased by 2.5% when intercropped with NamChe 5 rice. During 2025, a decline in soybean grain yield was observed under NERICA 1 (36%), Namche 3 (29%), NERICA 10 (28%), NERICA 4 (26%) and Namche 5 (4.6%) component crops.

3.3 Tillers, Panicles Per Plant, Grains Per Panicle, and Yield for Rice During 2024 and 2025

The results on tillers, panicles per plant, grains per panicle and rice grain yield during 2024 and 2025 are given in Table 3. Introduction of soybeans intercrops in rice did not influence the number of tillers and panicles per rice plant during 2024 and 2025.

Tiller numbers reduced numerically due to the introduction of soybean intercrops for NERICA 4 rice (23%), NERICA 1 (13%), NamChe 3 (7%), NERICA 10 (7%) and NamChe 5 (6%) during 2024. During 2025, tiller reductions were under intercrop NERICA 1 (20%), NamChe 3 (22%), NERICA 4 (13%), NERICA 10 (4%) and NamChe 5 (6%). Numerical reductions in panicles per plant were also recorded under NERICA 4 (10 & 13%), NERICA 1 (7 & 8.3%) and in NERICA 10 (8 & 6%), NamChe 3 (2% & 9%) and Namche 5 (7.2%) due to intercropping during 2024 and 2025, respectively. Sole and intercrop NERICA 1 produced significantly ($P \leq 0.05$) lower grains per panicle during 2024 and 2025. Significantly ($P \leq 0.05$) lower grains per panicle were similarly recorded under sole Namche 3, intercrop NamChe 5 and intercrop NERICA 10 treatments during 2025. NERICA 1 intercropped with soybeans recorded significantly lower grain yield than other treatments during both years.

3.4 1000-grain Weight

There were significant differences in 1000 grain weight among the treatments (Fig. 3). Namche 3 recorded significantly ($P \leq 0.05$) higher 1000 seed weight (25.4 gm), followed by Namche 5 (25 gm) and NERICA 4 (24 gm). Significantly ($P \leq 0.05$) lower but similar 1000 grain weight (23 g) was observed under NERICA 1 and 10 as indicated by the error bars in the figure.

3.5 Competitive Indices

3.5.1 Land Equivalent Ratios during 2024

The data on land equivalent ratios (LER) for rice and soybean intercrops during 2024 are indicated in Table 4. Introduction of legume intercrops in rice during 2024 and 2025 significantly ($P \leq 0.05$) reduced the partial land equivalent ratios (pLER) of rice to less than unity. During 2024, the pLER for rice was high for NamChe 3 (), .98). NERICA 1 (0.97), NERICA 4 (0.95) and NERICA 10 (0.94) but low for NamChe 5 (0.85). On the contrary, Soybean intercropped in NamChe 5 rice scored significantly ($P \leq 0.05$) higher pLER (1.02) above unity, which was followed by soybean intercrop in NERICA 4 (0.79) and NamChe 3 (0.77). Soybean intercropped in NERICA 10 and NERICA 1 recorded low pLER of 0.66 and 0.49, respectively. During 2024, significantly ($P \leq 0.05$) higher combined LER (cLER) were under NamChe 5 rice + Soybean (1.87) and NamChe 3 rice + Soybean (1.75), which were at par, followed by NERICA 4 rice + Soybean (1.74) and lower under NERICA 10 rice + Soybean (1.50) and NERICA 1 rice + Soybean (1.46).

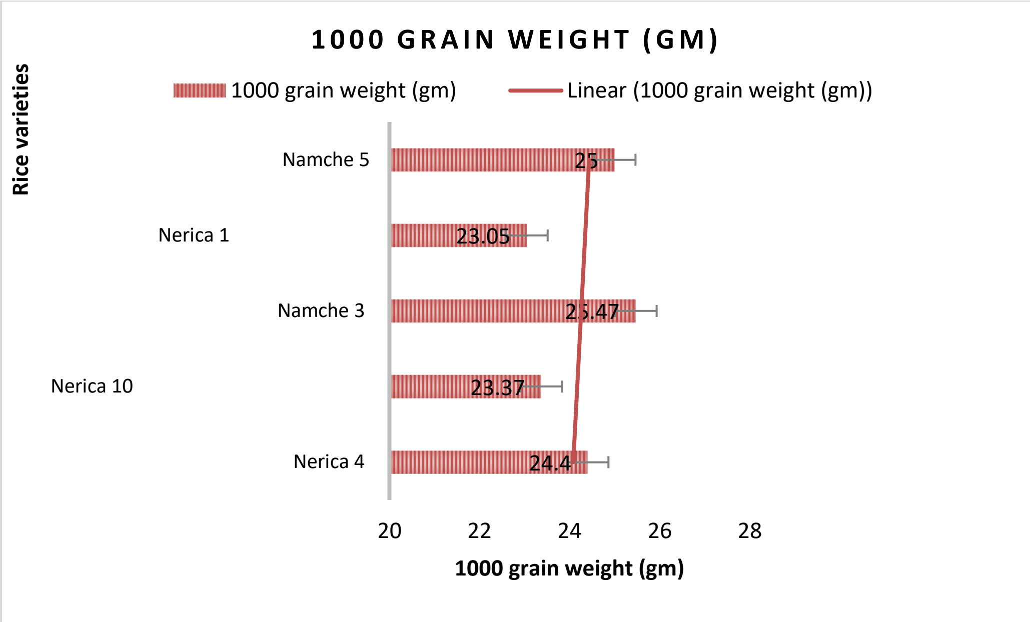

Fig. 3. 1000 seed weight for the rice varieties

3.5.2 Land Equivalent Ratios During 2025

The pLER for rice intercropped with soybean significantly (P≤0.05) differed during 2025 (Table 4). High pLER were recorded for NamChe 3 (0.97), NERICA 4 and NERICA 10 (0.91) rice. Lower pLER for soybean intercrops were under NERICA 1 rice (0.86) and NamChe 5 (0.81) rice. The pLER for soybean was significantly (P≤0.05) high (0.95) under intercropping with NamChe 5 rice, followed by soybean in NERICA 4 (0.74) and in NERICA 10 (0.72) and NamChe 3 (0.71), which were at par. The combined LER (cLER) for NamChe 5 rice + soybean (1.76) and NamChe 3 + soybean (1.73) treatments were significantly (P≤0.05) higher than other (Nerica) treatments. NERICA 4 rice + Soybean (1.65) and NERICA 10 rice + Soybean (1.63) registered low cLER, while NERICA 1 rice + Soybean produced significantly (P≤0.05) lower cLER.

3.5.3 Area Time Equivalent Ratio, Land Equivalent Coefficient, Rice Equivalent Yield and Partial Yield Difference

The Area time equivalent ratio (ATER), land equivalent coefficient (LEC), rice equivalent yield (REY) and partial yield difference (PYD) data for 2024 and 2025 are indicated in Table 5.

3.5.3.1 Area Time Equivalent Ratio

The results (Table 5) indicated that the introduction of soybean in rice significantly produced higher (P<0.001) ATER for NERICA 1 rice + soybean (1.78 & 1.27), NERICA 10 rice + soybeans (1.28) and NamChe 3 + soybean (1.27 & 1.37) during 2024 and 2025. Intercropping of soybean in NERICA 4 and NamChe 5 recorded low ATER.

3.5.3.2 Land equivalent coefficient

The data in Table 5 shows that intercropping soybean in NamChe 5 gave significantly (P<0.001) higher (0.87) land equivalent coefficient (LEC). This was followed by NamChe 3 or NERICA 4 intercropped rice (0.75). Lower LEC were observed under soybean intercropped in NERICA 10 (0.62) and NERICA 1 (0.47).

3.5.3.3 Rice Equivalent Yield

The rice equivalent yield (REY) for 2024 and 2025 is presented in Table 5. Soybean intercrop with NamChe 5 recorded significantly (P>0.05) high (<0.001) REY during 2024 (1.05 Mt Ha^{-1}) and 2025 (1.07 Mt Ha^{-1}). This was followed by REY under Nerica 4 + Soybean (0.80 Mt Ha^{-1} (2024) and 0.83 Mt Ha^{-1} (2025) and NamChe 3 + Soybean (0.79 Mt Ha^{-1}. The REY for NERICA 10 + Soybean (0.67 & 0.80 Mt Ha^{-1}) and NERICA 1 + Soybean (0.50 & 0.71 Mt Ha^{-1}) were significantly (P<0.05) lower.

Table 1. Plant height, leaf length, leaf width and tillers per plant during 2024 and 2025

Treatment	**2024**				**2025**			
	Plant height (cm)	**Leaf length(cm)**	**Leaf width (cm)**	**Tillers plant^{-1}**	**Plant height (cm)**	**Leaf length (cm)**	**Leaf width (cm)**	**Tillers plant^{-1}**
NERICA 4 Sole	73.65b	41.60a	1.68	6.17	74.57	41.17a	1.54 1.46	6.17
NERICA 4 + Soybeans	76.55a	45.90a	1.51	4.74	75.87	44.54a	1.50	5.07
NERICA 10 + Soybeans	78.45a	29.77b	1.83	5.72	79.27	31.80b	1.59	4.67
Namche 3 + Soybeans	82.77a	50.70a	1.48	4.97	84.85	47.33a	1.21	4.85
NERICA 1 Sole	68.80b	35.10b	1.50	6.15	71.33	34.00b	1.67	5.20
NERICA 10 Sole	76.17a	31.38b	2.11	6.14	76.87	30.73b	1.44	4.87
Namche 3 Sole	79.25a	44.00a	1.73	5.35	81.40	40.60a	1.06	6.23
Namche 5 + Soybeans	76.28a	43.00a	1.00	5.38	77.33	42.30a	1.35	5.73
Namche 5 Sole	72.95b	37.12a	1.34	5.70	74.20	36.80a	1.50	6.07
NERICA 1 + Soybeans	72.55b	42.00a	1.33	5.70	77.33	38.15a		5.27
P-value	0.03	<0.001	NS	NS	NS	<0.001	NS	NS
LSD (P=0.05)	8.03	9.70	0.99	1.53	9.90	11.70	1.55	2.12
CV (%)	6.8	8.4	21.5	16.1	6.3	10.3	22.7	19.1

Values with different letters in a column are significantly different at P≤ .05

Table 2. Plant height, pods per plant and grain yield for Soybean during 2024 and 2025

	2024			**2025**		
Treatment	**Plant height (cm)**	**Pods plant^{-1}**	**Yield (Mt ha^{-1})**	**Plant height (cm)**	**Pods plant^{-1}**	**Yield (Mt ha^{-1})**
Sole Soybean	76.3	57.4	1.19	75.6	58.1	1.30
Soybean in NERICA 4	86.2	40.6	0.94	84.3	45.5	0.96
Soybeans in NERICA 10	76.8	52.8	0.78	75.9	46.9	0.93
Soybean in Namche 3	84.2	48.6	0.92	84.4	40.8	0.92
Soybean in Namche 5	94.3	40.2	1.22	84.6	49.3	1.24
Soybeans in NERICA 1	76.9	52.4	0.58	76.7	41.5	0.83
P-value	NS	NS	NS	NS	NS	NS
LSD (P=0.05)	14.56	17.8	1.12	13.3	19.1	1.14
CV (%)	12.50	25.6	39.9	11.3	16.3	46.5

Values with different letters in a column are significantly different at P≤ .05

Table 3. Tillers, Panicles per plant, grains per panicle, and yield for Rice during 2024 and 2025

Treatment	**2024**				**2025**			
	Tillers plant^{-1}	**Panicles plant^{-1}**	**Grains panicle^{-1}**	**Yield (Kg ha^{-1})**	**Tillers plant^{-1}**	**Panicles plant^{-1}**	**Grains panicle^{-1}**	**Yield (Kg ha^{-1})**
Nerica 4 Sole	6.17	6.20	146.2a	1.43a	6.17	6.20	160.3a	2.10a
NRC 4 + S/beans	4.74	5.58	139.6a	1.16a	5.07	5.37	153.0a	1.91a
NMC 3 + S/beans	4.97	5.13	122.2a	1.02a	4.85	5.80	130.5a	1.93a
NERICA 10 Sole	6.14	6.45	139.8a	1.30a	4.87	5.55	129.6a	1.95a
NMC 3 Sole	5.35	5.62	124.0a	1.20a	6.23	5.93	122.6b	2.00a
NRC 10 + S/beans	5.72	5.95	132.1a	1.13a	4.67	5.20	117.3b	1.77a
NRC 1 Sole	6.15	6.00	110.0b	0.94a	5.20	5.90	104.8b	1.13a
NMC 5 Sole	5.70	5.60	125.8a	1.07a	6.07	5.50	127.8a	1.57a
NMC 5 + S/beans	5.38	5.20	128.3a	0.91a	5.73	5.10	123.7b	1.27a
NRC 1 + S/beans	5.38	5.47	106.7b	0.80b	4.17	5.50	100.2b	0.97b
P-value	NS	NS	0.04	0.05	NS	NS	0.005	0.04
LSD (P=0.05)	1.53	1.10	29.96	0.55	2.12	1.73	32.7	0.98
CV (%)	16.1	11.5	14.2	28.6	19.1	14.5	12.5	35.6

Values with different letters in a column are significantly different at P< .05. NS = Not Significant.
NRC = Nerica. NMC = NamChe, S/bean = Soybean Mak 4. Kg ha^{-1}= Kilograms per hectare

Table 4. Land equivalent ratio as influenced by intercropping

	2024			2025		
Treatment	**pLER rice**	**pLER Soybean**	**LER/cLER**	**pLER rice**	**pLER Soybean**	**LER/cLER**
NERICA 4 rice + Soybean	0.95a	0.79b	1.74b	0.91a	0.74b	1.65b
NERICA 10 rice + Soybean	0.94a	0.66c	1.50c	0.91a	0.72b	1.63b
NamChe 3 rice + Soybean	0.98a	0.77b	1.75a	0.97a	0.71b	1.68a
NERICA 1 rice + soybean	0.97a	0.49d	1.46d	0.86b	0.64c	1.50c
NamChe 5 rice + Soybean	0.85b	1.02a	1.87a	0.81c	0.95a	1.76a
P-value	0.001	0.001	<0.001	<0.001	<0.001	<0.001
LSD (P=0.05)	0.11	0.11	0.12	0.07	0.09	0.09
CV (%)	6.90	5.40	5.40	4.70	8.0	4.30

Values with different letters in a column are significantly different at P< 0.05, LER- land equivalent ratio, pLER – Partial land equivalent ratio, cLER – Combined land equivalent ratio.

3.5.3.4 Partial Yield Difference

The partial yield difference (PYD) for rice in Mt Ha^{-1} as presented in Table 5 was high for NERICA 4 + Soybean (-0.27 & -0.19) and NERICA 1 + Soybean (-0.14 & - 0.30), and during 2024 and 2025, followed by NERICA 10 + Soybean (-0.17 & -0.18). The PYD scores, however, declined to low levels for rice under NamChe 5 + Soybean (-0.15 & – 0.16) and NamChe 3 + Soybean (-0.18 -0.07) during both years. The PYD for soybean was high due to intercropping for NERICA 1 + Soybean (-0.61 & - 0.47), NERICA 4 (-0.25 &- 0.34) and NERICA 10 (-0.27 & -0.37) but was low for NERICA 3 (-0.28) and Namche 5 (-0.03 & -0.05).

Table 5. Indices for rice intercropped with soybeans during 2024 and 2025

Cropping system	**Growing season**	**cLER**	**ATER**	**LEC**	**REY**	**PYD ($Mtha^{-1}$)**	
						Rice	**Soybean**
Soybean Sole	(2024)	-	-	-	-	-	-
	(2025)	-	-	-	-	-	-
NERICA 1 +	(2024)	1.46e	1.78a	0.47d	0.50d	-0.14c	-0.61a
Soybean	(2025)	1.50e	1.27b		0.71c	-0.30a	-0.47b
Sole NERICA 1	(2024)	-	-	-	-	-	-
rice	(2025)	-	-	-	-	-	-
NERICA 4 +	(2024)	1.74c	1.20c	0.75b	0.80b	-0.27a	-0.25e
Soybean	(2025)	1.65d	1.23c		0.83b	-0.19b	-0.34d
Sole NERICA 4	(2024)	-	-	-	-	-	-
rice	(2025)	-	-	-	-	-	-
NERICA 10 +	(2024)	1,50e	1.28b		0.67c	-0.17b	-0.27e
Soybean	(2025)	1.63d	1.24c	0.62c	0.80b	-0.18b	-0.37c
Sole NERICA 10	(2024)	-	-	-	-	-	-
rice	(2025)	-	-	-	-	-	-
NamChe 3 +	(2024)	1.75b	1.27b	0.75b	0.79b	-0.18b	-0.28e
Soybean	(2025)	1.68b	1.37b		0.79b	-0.07d	-0.28c
Sole NamChe 3	(2024)	-	-	-	-	-	-
rice	(2025)	-	-	-	-	-	-
NamChe 5 +	(2024)	1.87a	0.83e	0.87a	1.05a	-0.16b	-0.03f
Soybean	(2025)	1.76b	0.85e		1.07a	-0.15b	-0.06f
Sole NamChe 5	(2024)	-	-	-	-	-	-
rice	(2025)	-	-	-	-	-	-
P-value		<0.001	<0.001	<0.001	<0.001	<0.001	0.002
LSD (P≤0.05)		0.08	0.04	0.04	0.04	0.03	0.05
CV (%)		4.0	3.7	4.5	5.2%	8.0	6.0

Values with different letters in a column are significantly different at P<0.05, Mt Ha^{-1} = metric tons per hectare, ATER = Area time equivalent ratio, LEC = Land equivalent coefficient, REY = rice equivalent yield, PYD = Partial yield difference.

3.5.4 Pooled Analysis of Yield, Total Rice Grain Yield Equivalent, Competitive Ratio, Competitive Index, Monetary Advantage Index, Income Equivalent Ratio and Aggressivity During 2024 and 2025

3.5.4.1 Pooled Yield Analysis for 2024 and 2025

The pooled rice yield analysis for 2014 and 2025 is indicated in Table 6. The rice yield was higher (<0.001) in 2025 than in 2024 under all treatments. Sole and intercropped NamChe 3, sole and intercropped NERICA 4, besides sole NERICA 10 rice produced significantly (P>0.05) high and similar rice grain yield to other treatments. Lower rice yield was recorded under sole NamChe 5 rice (1.57) and NamChe 5 + soybean (1.27), sole NERICA 1 rice (1.13) and NERICA 1 + Soybean (0.97). During 2024 and 2025, the soybean grain yield was high for the sole crop (1.19 &1.30 Mt Ha^{-1}) and NamChe 5 + Soybean (1.22 & 1.24 Mt Ha^{-1}), which were similar. Lower legume yield was recorded for NERICA 4 + Soybean (0.94 &0.96 Mt Ha^{-1}) and NamChe 3 + Soybean (0.92 Mt Ha^{-1}) with significantly lower soybean yield observed under Nerica 1 + Soybean intercropping (0.58 & 0.83 Mt Ha^{-1}) and NERICA 10 + soybean (0.78 & 0.93 Mt Ha^{-1})

3.5.4.2 Total rice grain yield equivalent

All the intercropping treatments resulted in substantially higher total rice grain yield equivalent (TRGYE) than sole rice during 2024 and 2025, and with higher TRGYE in 2025 than 2024 (Table 6). The highest and similar TRGYE were recorded under Nerica 4 + soybean (2.72 Mt Ha^{-1}), NamChe 3 + soybeans (2.74 Mt Ha^{-1}), Nerica 10 + Soybean (2.57 Mt Ha^{-1}) and NamChe 5 + Soybean (2.34 Mt Ha^{-1}) intercropping systems during 2025 in descending order. Lower TRGYE were recorded under NERICA 1 rice intercropped with soybean during 2024 and 2025.

3.5.4.3 Competitive ratio

The data in Table 6 shows that the Competition Ratio (CR) was significantly high (<0.001) under Nerica 1 intercropped with soybean (1.98 & 1.34) during 2024 and 2025. This was followed by NERICA 10 (1.42 & 1.26) and NamChe 3 rice intercropped with soybeans (1.27 & 1.37). A low CR was recorded for NERICA 4 + Soybean (1.20 & 1.23), with the lower CR values under NamChe 5 (0.83 & 0.85).

3.5.4.4 Competitive Index

During 2024 and 2025, the Competitive Index (CI) significantly (<0.001) differed (Table 6). High values were recorded under NERICA 1 intercropped with soybean (1.40 & 0.95), soybean intercropped in NERICA 10 (1.0 & 0.89) and NamChe 3 rice + soybean (0.90 & 0.97).

3.5.4.5 Monetary Advantage Index

The results in Table 6 indicate that NamChe 5 rice + soybean (0.46 & 0.43) and NamChe 3 (0.43 & 0.40) recorded higher (<0.001) MAI than other treatments during 2024 and 2025. This was followed by Nerica 4 + Soybean (0.43 & 0.39), and lower MAI were under NERICA 10 (0.33 & 0.39) and NERICA 1 (0.32 & 0.33) intercropping systems.

3.5.4.6 Income Equivalent Ratio

The income Equivalent Ratio (IER) significantly increased for soybeans intercropped in NamChe 5 rice (0.94 & 0.82) for 2024 and 2025 (Table 6). High IERs were similarly recorded for NamChe 3 (0.87), NERICA 4 (0.86 & 0.85) and NERICA 10 (0.82 & 0.83). NERICA 1 intercropped with soybean gave the lowest IER (0.59 & 0.75) for 2024 and 2025.

3.5.4.7 Aggressivity

During 2024 and 2025, NamChe 5 + Soybean (-0.6 & -0.65) recorded higher aggressivity (A) than other intercropping systems (Table 6). This was followed by NERICA 1 rice intercropping system (-0.31 to -0.28) and NERICA 4 (-0.23 and -0.24) intercropping systems. The lowest aggressivity was with the NERICA 10 + soybean intercropping system.

Table 6. Pooled yield, total rice grain yield equivalent, competitive ratio, competitive index, monetary advantage index, income equivalent ratio and aggressivity during 2024 and 2025

Cropping system	Growing season	Pooled analysis of Yield (Mt Ha^{-1})		TRGYE (Mt Ha^{-1})	CR/CI		MAI	IER	AGGRESIVITY
		Rice	Legume		CR	CI			Rice + Legume
Soybean Sole	(2024)	-	1.19a	-	-	-	-	-	
	(2025)	-	1.30a	-	-	-	-	-	
NERICA 1 + Soybean	(2024)	0.80f	0.58d	1.31g	1.98a	1.40a	0.32c	0.59d	-0.31b
	(2025)	0.97e	0.83c	1.68f	1.34b	0.95b	0.33b	0.75c	-0.28b
Sole NERICA 1 rice	(2024)	0.94f	-	-	-	-	-	-	
	(2025)	1.13e	-	-	-	-	-	-	
NERICA 4 + Soybean	(2024)	1.16e	0.94b	1.96d	1.35b	0.87b	0.43a	0.86b	-0.23b
	(2025)	1.91a	0.96b	2.74a	1.33b	0.85b	0.39b	0.85b	-0.24b
Sole NERICA 4 rice	(2024)	1.43c	-	-	-	-	-	-	
	(2025)	2.10a	-	-	-	-	-	-	
NERICA 10 + Soybean	(2024)	1.13e	0.78c	1.80e	1.42b	1.00b	0.33b	0.82b	-0.06c
	(2025)	1.77b	0.93b	2.57b	1.28c	0.89b	0.39b	0.83b	-0.17c
Sole NERICA 10 rice	(2024)	1.30d	-	-	-	-	-	-	
	(2025)	1.95a	-	-	-	-	-	-	
NamChe 3 + Soybean	(2024)	1.02e	0.92b	1.81e	1.27c	0.90b	0.43a	0.87b	-0.24b
	(2025)	1.93a	0.92b	2.72a	1.26c	0.97b	0.40a	0.87b	-0.12c
Sole NamChe 3 rice	(2024)	1.20d	-	-	-	-	-	-	
	(2025)	2.00a	-	-	-	-	-	-	
NamChe 5 + Soybean	(2024)	0.91f	1.22a	1.96d	0.83d	0.59c	0.46a	0.94a	-0.60a
	(2025)	1.27d	1.24a	2.34c	0.85d	0.60c	0.43a	0.82b	-0.65a
Sole NamChe 5 rice	(2024)	1.07e	-	-	-	-	-	-	-
	(2025)	1.57c	-	-	-	-	-	-	-
P-value		<0.001	<0.001	<0.001	<0.001	<0.001	0.004	<0.001	<0.001
LSD (P≤0.05)		0.16	0.12	0.05	0.07	0.15	0.06	0.06	0.13
CV (%)		5.6	5.6	4.5	4.8	10	6.2	5.2	15.7

Values with different letters in a column are significantly different at P<0.05, TRGYE = Total rice grain yield equivalent. CR= Competitive ratio, CI= Competitive index, MAI = monetary advantage index, IER= Income equivalent ratio, Mt Ha^{-1} = Metric tons per hectare

4. Discussion

4.1 Plant Height, Leaf Length, Leaf Width and Number of Tillers Per Plant for Rice During 2024 and 2025

There was a significant increase in the height of rice crops intercropped with Mak 4 soybean, which was similar to the height of sole NERICA 10 and sole NamChe 3 rice. This may be attributed to changes in the crops' competition dynamics for solar radiation, nutrients and space. Intercrops grow taller because they compete vertically for sunlight, a morphological plasticity (adjustment of plant architecture in response to neighbors) triggered by competition–induced conditions like increased density effects and higher transpiration efficiency. Higher plant density may also intensify asymmetric competition for light, space, soil nutrients and water. Stem elongation is also associated with the sensing of plants for shade through changes in the red (R): far red (FR) light ratio and responds by stem elongation in a process called shade avoidance response. When a plant is shaded, chlorophyll in neighboring leaves absorbs red (R) light and reflects (FR) light. This decreases the R: FR ratio, which activates phytochrome receptors. The activated phytochrome triggers shade-avoidance responses and causes stem elongation. Practically, as R/FR decreases (more far red), the plants elongate. The stem elongation may also be attributed to the production of more gibberellins GA1, GA3) and auxins (IAA) under shading or stress conditions, which promotes stem internodes elongation. Sometimes, a companion crop may alter the micro-climate (humidity & temperature), which encourages taller growth of the other crop. The increased rice plant height, therefore, could have resulted from a higher plant population that possibly enhanced more efficient absorption of solar radiation under dense shading and competition between rice and the soybean crop for nutrients planted in the East-West row direction. It has been reported that under nutrient stress, plants' stems elongate more than branches to outcompete neighbors. East-West rows allow uniform light on the entire crop canopy throughout the day, and this gives more efficient photosynthesis in the C3 pathway, boosts photosynthesis and growth, especially in the lower leaves and enhances crop growth and reduces photorespiration. When the canopy growth is uniform, as occurs in the east-west direction, plants grow more uniformly, flowering is synchronized, and maturity is even. Kaiira et al. (2023) reported that rice and soybeans, being C3 crops, produced higher plant growth and grain yields in the EW row direction due to reduced weeds, with higher efficiency in utilizing Carbon dioxide and solar radiation.

The similar height for sole Nerica 10 and sole NamChe 3, to the height of similar intercropped rice varieties, may be attributed to the genetic characteristic of the two varieties that are taller than NERICA 1 rice. Sole NERICA 1, Sole NERICA 4, Sole NamChe 5 and NERICA 1 + soybeans produced significantly ($P \leq 0.05$) shorter rice plants. Sole crops exhibit reduced competition pressure, grow in a uniform environment without shading, and have little or no vertical competition. Sole crops usually have optimal spacing, giving each plant enough light, nutrients and moisture. The R: FR light signal under sole crops is minimal, and therefore plants remain shorter and sturdier. Sole plants, therefore, prioritizes stem strength and leaf development and not stem elongation. The non-significant rice height during 2025 may be attributed to the possible favorable weather conditions of higher (850 mm) seasonal rainfall (Fig. 2), associated with possible lower and favorable temperatures and humidity, which are conducive for C3 rice crops. Results from this study indicated increased leaf length for rice during the 2 years due to intercropping with soybean, except for intercropped Nerica 10. The increase in leaf length was possibly a response to competition for solar radiation and other resources above the ground, as explained earlier for plant height. NERICA 10 rice has an erect leaf angle (0-30^0), which stands almost upright compared to the other tested rice varieties with semi-erect (30-45^0) and horizontal leaf angles (45-90^0). NERICA 10 rice also has a wider lamina than the other varieties with linear, lanceolate and broad leaves. The leaf shape and angle of attachment to the stem for NERICA 10 could have enabled the plant to tap adequate solar radiation with minimal competition. This canopy architecture maximize light penetration into the canopy for high plant density without shading and gives high yields. Erect leaves allow higher density planting than broad leaves and respond better to nitrogen with reduced lodging. NERICA 1 and NERICA 10 rice have genetically shorter leaf length. Leaf width and tillers for rice are highly genetically controlled and less sensitive to moderate competition, and this is the possible reason that they were not significant during 2024 and 2025.

4.2 Plant Height and Pods Per Plant and Yield for Legumes During 2024 and 2025

There was no significant change in soybean plant height due to its introduction in all treatments. This may be attributed to the rapid early growth, strong apical dominance and genetically fixed plant height range for the legume. Plant height, being strongly genetically controlled, may not have been reduced due to moderate competition from rice plants. Rice leaves are narrow and form a vertical canopy, which allows light penetration, creates little horizontal shading, especially in the EW orientation, and thus possibly has very little influence on light reaching the component soybean-legume crop.

The observed results may also be associated with the different complementary root systems of rice (fibrous & shallow) and soybean (deeper tap root) that could have explored different soil layers, and legume component crops did not suffer water or nutrient stress that would limit height. It is also postulated that the legume component crop depends less on soil nitrogen because of Biological nitrogen (N) fixation. Therefore, even if rice competed for soil nutrients, soybeans could have got enough N to maintain normal growth. The non-significant soybean height could also be attributed to proper spacing under paired rows (40/20 x 12.5 cm) that possibly reduced crowding with lower competition pressure, resulting in stable soybean height. The results may also be associated with a lack of strong overlap of competition peaks for legumes and cereals to cause above-ground competition.

The non-significant change in soybean pods per plant under intercropping with rice could be attributed to the paired row arrangement that allowed better light interception and branching with minimal competition between the component crops. Pod formation in soybean is influenced by genetic factors, but light availability, which is influenced by plant density and spacing, which influence soil moisture, temperature and weeds, besides the availability of Nitrogen. Phosphorus, Potassium and micronutrients are among the strongest determinants of pod number. Liu et al. (2011) reported that the reduction of total soluble sugar concentration was directly responsible for lower pod number in soybeans under shading conditions. The observed similar and non-significant soybean yield is associated with the non-significant plant height and pods per plant. Taller plants usually branch more with a higher number of nodes, develop more pods, which is the most important yield component, produce more seeds and give higher grain yield. Numerically higher soybean plant height was in the intercropped plots, but pods per plant and grain yield were reduced under intercropping ecosystems. The differences, however, were not significant ($P \geq 0.05$), indicating that intercropping did not meaningfully affect the factors. This suggests that the soybean plants responded similarly across treatments and competition, management and variety differences were not strong enough to alter soybean height, pods per plant and grain yield, which are genetically stable and less responsive to treatments.

4.3 Tillers, Panicles Per Plant, Grains Per Panicle, and Yield for Rice During 2024 and 2025

There was no significant change in the number of tillers and panicles per rice plant due to the introduction of soybeans intercrop during both years. This may be associated with the different ecological niches for the two crops, which could have allowed the two crops to coexist without strong competition. The component crops also have special separation of the rooting systems, with a fibrous root system for rice and a deep taproot system for soybeans, which could have minimized root competition during the tillering phase. Since rice tillers early (2-5 weeks after planting) while the soybeans are still small with low biomass, rice possibly completed most of its tiller formation before soybeans had become a strong competitor. The non-significant tillering and panicle formation for rice may also be attributed to the ability to fix atmospheric nitrogen through rhizobia. This reduces direct competition for nitrogen with rice, and since tillering and panicle formation are highly dependent on nitrogen, the rice crop could not suffer a deficit. Zhao. et al. (2022) reported that Nitrogen applications significantly contributed to superior tillers of good quality, which made a great contribution to rice yield. Wang et al. *(*2018) observed that Nitrogen supply promoted rice spikelet differentiation and degeneration. Similar observations were made by Yang et al. (2017). In a similar study, Huang et al. (2020) similarly indicated that panicle number is essential for achieving high grain yields in machine-transplanted hybrid rice.

The slight, but non-significant, reduction in rice tillers and panicles per plant under intercropping suggests the presence of mild competition from soybean for resources such as light and nutrients. This may also be associated with slight competition within natural variability, but not strong enough to statistically affect rice tiller and panicle production. The non-significant tillers and panicles for rice due to inter-cropping may similarly be ascribed to adequate space for component rice and soybean crops under the adopted paired rows (40/20 x 12.5 cm) of rice that allows enough space and resources for rice to tiller normally, given its strong compensatory tillering ability. The number of grains per panicle is a critical yield component in rice and reflects the crop's ability to convert assimilates into reproductive structures. In sole and intercropped rice systems, grains per panicle are influenced by nutrient availability and competition. The reduced grains per panicle for sole and intercropped NERICA 1 during 2024 and 2025, besides sole NamChe 3, intercrop NamChe 5 and intercrop

NERICA 10 during 2025, may be associated with mild competition for non-nitrogen factors such as light interception and water availability, which can limit tillering, spikelet formation or panicle branching. In sole cropping, rice roots dominate the soil profile, reducing variability in water uptake. The lower grains per panicle could thus be attributed to mild late–season competition for light or nutrients and water that possibly affected spikelet fertility but not spikelet initiation. The grains per panicle or unit area directly represent the number of sinks that fill to produce the grain yield. The reduced grains per panicle or unit area observed under intercropped NERICA 1 greatly contributed to the significantly lower grain yield for the intercropped NERICA 1 rice relative to the other treatments that were similar. Grain yield is a function of the number of productive tillers/ panicles/ pods and spikelet percentage and shows the greatest variability under field conditions.

4.4 1000 Grain Weight

The 1000 grain weight (TGW) differed among the treatments, with NamChe 3 recording significantly ($P \leq 0.05$) higher TGW (25.4 g), followed by NamChe 5 (25 g) and NERICA 4 (24 g). Significantly ($P \leq 0.05$) lower but similar TGW (23g) were observed under NERICA 1 and 10. TGW is influenced by genetic factors, which may be varietal characteristics such as grain length, width and thickness. Other factors include the genetic potential for grain filling rate and duration, hull size and capacity of the spikelet to accumulate starch due to competition for light, water or nutrients. Singh et al. (2024) linked TGW to grain filling efficiency and endosperm composition. The genetic potential for grain filling rate is determined by panicle architecture, which affects assimilate distribution among spikelets. Rice grain filling is also affected by source-sink relationships. The photosynthetic capacity, leaf area and health, carbohydrate reserves in stems, number of grains per panicle and grain size influence the filling rate. Subedi et al. (2024) associated TGW with starch accumulation or grain sink strength. Similarly, grain filling rate affects TGW and is determined by nitrogen, which enhances photosynthesis, potassium that improves assimilate translocation, phosphorus, which supports energy transfer ATP) needed for grain development and micronutrients (Zn, Fe &B) involved in enzyme activation and hormone regulation. Fageria et al. (2014) associated increased TGW with higher nutrient uptake and increased absorption of solar incident radiation for photosynthesis. The availability of water to support photosynthesis and assimilate transport, optimum temperatures (22-28^{0}C), and crop management practices such as plant density could have affected TGW for the different treatments.

4.5 Competitive Indices

4.5.1 Land Equivalent Ratios During 2024 and 2025

A crop with a relatively large land equivalent ratio (LER) may be competitively successful and often shows canopy advantage, e.g. greater height or biomass allocation. The partial LERs (pLER) for intercropped rice were all less than unity during both cropping seasons, which implied that the intercrop components produced less yield per unit area than their sole crop (monocrop). This may be attributed to competition for light, nutrients, water and space. The high yield percentage of the sole rice recorded during the years under the intercropping systems of NamChe 3, NERICA 1, NERICA 4, NERICA 10 and NamChe 5 may be attributed to inefficient use of resources due to shade or reduced physiological performance. On the contrary, the introduction of soybean in NamChe 5 rice was quite advantageous as it produced higher (102 & 95%) soybean yield than the sole soybean. The results thus designated benefits for soybeans from intercropping with NamChe 5 rice, possibly arising from positive and beneficial interspecific interactions. This yield advantage could be attributed to more efficient utilization of light, water and nutrients during the growing season. Low soybean yield of sole crop harvest was under intercropping with NERICA 4 and soybean in NamChe 3, which gave low sole soybean yield during 2024 and 2025, respectively, while soybean intercropped in Nerica 10 and Nerica 1 recorded even lower yields of their sole crop yields in 2024. The lower yields are associated with inefficient utilization of resources (light, nutrients & water) due to shade or reduced physiological performance.

Significantly ($P \leq 0.05$) higher combined LER (cLER) under NamChe 5 rice + Soybean and NamChe 3 rice + Soybean were recorded during both 2024 and 2025, followed by NERICA 4 rice + Soybean, and this could be attributed to positive biological and ecological interactions with greater land use efficiency under intercropping. A farmer needs 87%, 75% and 74% more land under mono-cropping to achieve the intercrop yield received during 2024. This improved overall productivity and sustainability may be due to better suppression of weeds, improved soil health and higher system resilience. NamChe 5 rice + Soybean and NamChe 3 rice + Soybean had a stronger positive interaction and more efficient resource use compared to NERICA 4 rice + Soybean. The least productive systems were NERICA 10 rice + Soybean (cLER of 1.5 & 1.63) and NERICA 1 rice + soybean (1.46 & 1.5) for 2024 and 2025. The lower cLER may be associated with poor land use efficiency. Li et al. (2023) reported that intercropping performs well in producing a diverse set of crop products and performs almost similarly to the most productive component sole crop to produce raw products, while improving crop resilience, enhancing ecosystem services, and improving nutrient use efficiency. The results are supported by Erythrina et al. (2022), who reported that the rice–soybeans intercropping system recorded 54% higher yield advantage.

Advantages of land utilization of intercrops over monocultures that yielded a total LER of 1.58 were noted by Nassary et al. (2020), whereas the average PLER of individual beans was 1.53. The 3 intercropping systems, namely rice-beans, rice-groundnuts and rice-maize, led to more yield benefits based on the average LER of 1.5 obtained (Mugisha et al., 2020). Xu et al. (2020) reported an average LER for rice/soybean intercropping of 1.32±0.02, indicating a substantial land sparing potential of intercropping over sole crops. Similar combined LER of more than 1.0 were recorded under rice-legume intercrops, which significantly differed from the pLER (1.0) of sole conventional rice. Martin et al. (2018) revealed that when the same land area was managed in monoculture, intercrops produced 38% more gross energy (mean relative land output of 1.38) and 33% more gross incomes (mean relative land output of 1.33) on average, whilst using 23% less land (mean land equivalent ratio of 1.33). The results are supported by Hailu (2025), who reported that corn-soybean intercropping had higher land use efficiency and biological prowess (LER>1). According to Amanullah et al. (2016), intercropping of common bean under compost-treated plots had a higher LER of 1.14 and 1.07 as compared with sole cropping (1.0). The research by Oroka and Omoregie (2007) indicated LER between 1.79 and 2.30 for a rice-cowpea mixture at all levels of nitrogen and plant densities.

4.5.2 Area Time Equivalent Ratio, Land Equivalent Coefficient, Rice Equivalent Yield and Partial Yield Difference

4.5.2.1 Area Time Equivalent Ratio

Area time equivalent ratio (ATER) improves on LER by accounting for differences in crop duration. Introduction of soybean component in rice significantly produced higher ($P<0.001$) ATER for NERICA 1 rice + soybean, NERICA 10 rice + soybeans and NamChe 3 + soybean during 2024 and 2025. All intercropping combinations had ATER> 1.0, implying that they were more efficient than sole cropping systems. The results indicated that NERICA 1 rice + soybeans and NERICA 10 rice + soybeans showed strong complementarity, with the two systems having 78% and 27% more efficiency in land x time use during 2024 and 2025, respectively. The results imply that NERICA 1, NERICA 10 rice and NamChe 3 rice performed far better with respect to ATER under intercropping systems than NERICA 4 and NamChe 5 rice, which recorded lower ATER. Results are supported by Ozioma (2024), who recorded ATER between 1.23 and 1.50 for rice intercropped with soybeans in different row ratios.

4.5.2.2 Land Equivalent Coefficient

Intercropping soybean in NamChe 5, NamChe 3 and NERICA 4 gave significantly ($P<0.001$) higher land equivalent coefficient (LEC). Lower LEC were observed under NERICA 1 and 10 rice intercropped with soybean. Since the critical LEC threshold is 0.25, the results therefore indicate that all the intercrops were more productive than sole crops, but land was more efficiently used by NamChe 5 (87%), NamChe 3 (75%) and NERICA 4 (75%) when intercropped with Soybean. Based on the results, the above three mixtures were superior components to sole crops.

4.5.2.3 Rice Equivalent Yield

Introduction of soybean significantly increased (<0.001) rice equivalent yield (REY) for NamChe 5, NERICA 4 and NamChe 3 rice during 2024 and in 2025. The results showed ($P<0.05$) lower REY for NERICA 10 + Soybean and NERICA 1 + Soybean. The REY for all rice-soybean intercrop treatments was lower than the sole rice yield. This indicates that the reduction in rice grain yield under intercropping was not compensated for by the economic value of soybean yield. Poor soybean performance due to shading and competition, combined with relatively low soybean prices (3,500 Ush) relative to rice price (3,000 Ush), possibly limited its contribution to REY because of a low land use efficiency. In addition, the high yield of the sole rice crop set a strong benchmark, making it difficult for the intercrop to match its productivity when expressed in rice terms. Consequently, intercropping in this study did not provide a high economic advantage over sole rice production, but NamChe 5, NERICA 4 and NamChe 3 rice intercropped with soybeans were the most productive and profitable cropping systems.

4.5.2.4 Partial Yield difference

The partial yield difference (PYD) for rice obtained in 2024 and 2025 for both rice and soybeans was generally low and negative, indicating that intercropping caused only slight yield reductions relative to their respective sole crops. NamChe 3 rice recorded a slightly high yield reduction, while NamChe 5 rice had a lower yield reduction during 2024 and 2025. This indicated that the presence of soybeans exerted minimal competitive pressure on both rice varieties. The small magnitude of these negative values suggests that resource competition for light, nutrients, and moisture was limited, enabling rice to maintain yields close to those of its sole crop performance. The slightly lower PYD in NamChe 3 and NamChe 5 rice varieties further imply that the varieties may possess better morphological and physiological attributes, such as canopy structure, tillering ability, or nutrient uptake efficiency that enhance their complementarity in an intercropping system with soybeans. High soybean PYD were under NERICA 4, NERICA 10 and NERICA 1 rice for the two years. This is related to the higher rice and soybean yield reductions under their intercropping treatments and may be attributed to interspecific competition for light, nutrients, space and moisture due to poor morphological and physiological attributes. Soybean under all rice varieties also exhibited relatively low yield penalties. In NamChe 3 plots, for instance, soybean had a yield reduction of 0.28 Mt Ha^{-1}, indicating moderate competition, whereas soybean under NamChe 5 exhibited almost no yield loss during the two years. The low PYD values correspond closely with the land equivalent ratio (LER), which was far greater than 1.0 for the NamChe 3 (1.75 & 1.68) and NamChe 51.87 & 1.76) rice-soybean systems. An LER > 1 shows that the intercrop required less land to produce the same combined yield as the sole crops, confirming a biological yield advantage. The high LER observed in NamChe 3 and NamChe 5- soy intercrops align with the near–zero PYD for soybean, reinforcing that the variety mixture achieved superior complementarity and resource use efficiency.

The results also suggest that NamChe 3 may have been slightly more competitive for growth resources compared with NamChe 5, possibly due to differences in shading, plant height, or root competition. However, since the PYD for soybeans under NamChe 5 were almost negligible, this demonstrated that soybean performance under NamChe 5 rice was nearly equal to its sole crop yield. This extremely low yield difference highlights the high level of compatibility between Maksoy 4N and NamChe 3 and NamChe 5 rice, where the legume experienced minimal suppression, likely due to reduced shading and improved light penetration within the canopy. It should be noted that even when the PYD is low, the overall system may still provide greater advantage through higher total productivity as per the high LER (section 4.5.5) for NamChe 3 & 5 rice varieties, extra legume nitrogen benefit and higher economic returns. The low PYD for the two NamChe varieties also imply that the intercrop yields for both soybean component crops in NamChe3 and NamChe 5 rice varieties were close to their sole crop yields, demonstrating that the intercropping systems maintained crop performance while maximizing land use efficiency. The PYD results support the suitability of the Namche 3 + Mak 4N soybean and NamChe 5 + Maksoy 4N soybean intercropping systems. Overall, the low negative PYD values across the two NamChe rice and Maksoy 4 rice components indicated that the rice-soybean intercropping system was efficient and imposed only slight yield penalties on individual crops. These results reflect balanced interspecific interactions and complementary resource use patterns, which are desired characteristics for a productive and sustainable intercropping system. The minimal yield losses for NamChe 3 and 5 rice and the associated Maksoy 4N soybean intercrop further suggest that this combination offers a promising option for farmers aiming at maximizing land productivity, while maintaining stable component yields.

4.5.3 Pooled Yield analysis, Total Rice Grain Yield Equivalent, Competitive Ratio, Competitive Index, Monetary Advantage Index, Income Equivalent Ratio and Aggressivity during 2024 and 2025

4.5.3.1 Pooled Yield Analysis for 2024 and 2025

Pooled data analysis discloses if a treatment performs consistently across years under variable weather conditions. When the years are pooled, variation is better estimated and gives more accurate and reliable conclusions. Pooled years (2024 & 2025) data indicated a higher rice grain yield for 2025 than 2024 for all the treatments. This may be attributed to more favorable weather (rainfall, temperature, nutrient uptake) conditions as evidenced by higher rainfall during 2024 than 2025 (Section 2.1.2). Namche 3, NERICA 4 and NERICA 10 rice produced significantly ($P>0.05$) high rice grain yield during the 2 years. This may be attributed to the significantly ($P\geq0.05$) high rice grains per panicle, 1000 seed weight (Fig. 3), which contributed to grain yield under the treatments. This is evidenced and supported by results under separate years yield analysis (Section 3.3). Pooled data analysis indicated lower rice grain yield under Namche 5 rice and NERICA 1 rice, which may also be associated with the observed significantly low grains per panicle (Section 3.3) and 1000-grain weight (Fig. 3) under the treatments. Rice yield is a function of three components: number of panicles per unit area, number of grains per panicle and 1000-grain weight.

An increase in the number of grains per panicle directly increases the total grain output per plant, and consequently per hectare. In many rice varieties, yield differences are primarily attributed to variation in grains or spikelets per panicle rather than differences in plant population or grain size. Grains per panicle are an indicator of effective tillering and reproductive success. Low grain numbers may indicate stress at critical growth stages, resulting in spikelet abortion or incomplete panicle development. Rice has a compensation mechanism in the yield system between panicle density and the number of grains per panicle. When panicle density is high, the number of grains per panicle may reduce, with unfilled grains, lower 1000 grain weight, reduced effective grain number and vice versa. Genetic influence also determines the number of grains per panicle. NERICA rice varieties with long panicles may produce more grains per panicle than rice with short panicles. Maintaining good crop conditions during panicle initiation through grain filling is essential for optimizing grains per panicle and thus achieving maximum rice yield. When the tillers and panicles per panicle show no significant difference across treatments (Section 3.3), grains per panicle become the key variable determining yield differences. It is influenced by resource availability during the reproductive stage, compensation mechanism, panicle branching, environmental conditions and competition effects typical of intercropping.

4.5.3.2 Total Rice Grain Yield Equivalent

All the intercropping treatments resulted in substantially higher total rice grain yield equivalent (TRGYE) than sole rice during 2024 and 2025, because it converts all the yield of an intercropping system (Including soybean) into the equivalent of rice using market prices. The higher TRGYE during 2025 than 2024 may be ascribed to the higher rice and soybean harvests during 2025 (Sections 3.2 & 3.3), which were associated with favorable weather conditions (Rainfall during 2025 than 2024 (Section 2.1.2). TRGYE is influenced by agronomic, ecological, competitive and economic factors. Any reduction in rice or soybean grain yield due to competition for light, water, nutrients, etc., will reduce the TRGYE. The TRGYE recorded under intercropping systems were higher for NamChe 3 and NERICA 4 but lower for NamChe 5 and NERICA 10 during 2025. This may be attributed to reduced productivity due to declines in the number of productive tillers, panicles per unit area, grains per panicle, filled grains percentage and 1000 grain weight under the treatments. Lower TRGYE were recorded under NERICA 1 rice intercropped with soybean during 2024 and 2025. The soybean yield could have positively influenced the TRGYE. If soybean yield is high, it significantly raises the TRGYE even when rice yield is slightly reduced. Legume intercrop yield is affected by pods per plant, seeds per pod, plant height and light interception, nodulation efficiency and variety adaptability to intercropping conditions. The economic factors that influence TRGYE include the price of the component crops. TRGYE increases even when the physical yield is moderate. The adopted spatial arrangement (paired rows of rice) under the current study, plant population and variety architecture (erect or spreading) also could have affected the TRGYE. The different TRGYE recorded under NamChe 3, NERICA 4, NamChe 5 and NERICA 10 during 2025 may also be attributed to crop compatibility. Compatible crop combinations produce higher TRGYE. The results are supported by Kaiira et al. (2024), where high TRGYE were recorded under rice + soybeans intercropping system and associated with the high soybean yield. Increase in TRGYE as a result of intercropping was also reported by Rana et al. (2013).

4.5.3.3 Competitive Ratio

Competitive Ratio (CR) was significantly high (<0.001) and more than unity under NERICA rice varieties (NERICA 1, NERICA 4 and NERICA 10 rice) intercropped with soybeans. Lower CR were recorded for NamChe 3 and 5 (NamChe) rice varieties. The CR for NamChe 5 were low ($CR< 1.0$) during 2024 and 2025. When the $CR>1$, the crop is competitively superior with height dominance and usually grows taller than its sole crop because it invests in height to maintain dominance. Taller crops have greater photosynthetic nitrogen use efficiency, and the results in section 3.1 (2024) further support the findings under this study. Where the CR for rice was lower and moderately more than one in Namche 3 intercrops, during 2024 and 2025, the crop acted as a slightly stronger competitor, which explains the relatively larger soybean PYD (-0.28 Mt Ha^{-1}). In contrast, CR values close to 1 (0.83 & 0.85) in NamChe 5-soybean combinations indicated a more balanced competitive relationship. This CR near unity suggests equitable use of resources and reduced dominance, which is a desired trait for sustainable intercrop design. This interspecies balance is consistent with both the minimal soybean PYD (-0.03 & -0.06 Mt ha^{-1}) and the higher combined productivity implied by LER (1.75 &1.68) for NamChe 3 during 2024 and 2025, respectively. NamChe 5 similarly had a high LER of 1.87 and 1.76 during 2024 and 2025, respectively. Based on the results, NamChe 3 & 5 rice varieties and, to an extent, NERICA 4 rice, provided more conducive growth conditions for component crops. Little work has been reported on CR for rice and soybeans, but Kritamtini et al. (2025) reported maize and soybean as a better crop combination than upland rice– soybeans, maize-upland rice and maize-pea nuts.

4.5.3.4 Competitive Index

Introduction of soybeans in NERICA 1 OR NERICA 10 recorded higher competitive indices (CI) that were more than unity. This may be attributed to the faster growth during the early stages of rice (NERICA 1 & 10), which could have shaded the soybeans and rice, possibly also pre-empted soil nutrients. Rice becomes more competitive when it is taller than soybeans, has an erect but dense canopy and intercepts most of the light. The results are supported by the data (Section 3.1) that indicated significantly long leaf for NERICA 1 rice and the genetically erect-leaved and tall NERICA 10 with dense canopy. A vigorous rice variety will have a high CI. Rice, being a heavy nitrogen feeder, becomes more competitive when Nitrogen is plentiful. More nitrogen possibly boosted NERICA rice biomass and height, giving the cereal crop a competitive advantage. When the phosphorus or potassium levels are low, soybeans, which are sensitive to P deficiency, are disadvantaged, and rice dominates as nutrient imbalance usually favors cereals over legumes. The lower CI (CI<1) for all the other combinations, namely, NamChe 3, NamChe 5, and NERICA 4 rice intercropped with soybean, may be associated with the fast growth of the legume that could have limited the tillering of rice. Rice roots spread shallowly, while soybeans have deeper roots. Under drought conditions, soybeans access deeper moisture as the rice struggles. NERICA 1 and 10 matured earlier than soybean; therefore, soybean could have suppressed rice during grain filling, leading to suppression of physiological processes for grain filling rice crops. Since soybeans fix their own nitrogen, when nodulation is good, soybeans gain a competitive nitrogen advantage and become more dominant over rice. Little literature is available to support the results.

4.5.3.5 Monetary Advantage Index

Economic returns aligned with the biological indicators. NamChe 3 and NamChe 5 rice + soybean recorded higher (<0.001) Monetary Advantage indices (MAI) than other treatments during 2024 and 2025. Systems with high LER, particularly NamChe 3 and NamChe 5–soybean intercrops, generated high monetary returns due to the efficient conversion of land into marketable output. The minimal yield penalties (low PYD) for the 2 NamChe rice varieties, combined with improved total system productivity, translated into better land productivity and greater profitability per hectare. Even under NamChe 3 systems, where soybean PYD was slightly higher, overall economic returns still surpassed those of sole cropping due to the added value of soybean harvests and the efficient use of land resources. The lower MAI for NERICA 1, NERICA 4, and NERICA 10 intercropping systems could be attributed to lower LER for the crop combinations as indicated in section 3.5.2. Goshi (2004) found that when the LER were higher, there was a significant economic benefit expressed with higher MAI values. This reflects poor biological advantage as the intercrops compete strongly for resources. The low MAI may also be associated with a decline in the yield of one or both component crops, poor spatial arrangement, population imbalance or imbalanced fertilization. Reduced yield (LER) under the NERICA variety treatments may be due to shading effects, nutrient competition, water stress and poor variety compatibility. If the nitrogen level is too high, rice dominates and suppresses soybeans. Low nutrient availability lowers yield, reducing economic returns. Poor variety compatibility is another cause of low MAI. A short rice variety like Nerica 1 is easily overshadowed by soybeans. Similarly, a tall, aggressive rice variety like NamChe 3 and 5 (Section 3.1) could have easily dominated soybeans in the current study. The low MAI could also be attributed to low legume prices. The price ratio between crops disfavors the intercrop (legume), which had a low price. Thus, weak biological efficiency translates into low economic efficiency. The results are supported by Erythrina et al. (2022), who recorded high (USD 633 ha^{-1}) under rice-soybean intercropping. Khonde et al. (2018)

observed a relatively high MAI with Mudishi 3-soybean as an economic efficiency intercrop than soybeans and cowpeas + maize mixtures. The results are supported by Kamara et al. (2017), who reported high and positive MAI for all intercrops of maize-soybeans, showing yield and economic advantages compared to the sole cropping systems.

4.5.3.6 Income Equivalent Ratio

All the income Equivalent Ratios (IER) were less than one. Higher IER ratios were recorded for intercropped NamChe 5 rice, NamChe 3 and NERICA 4, while lower values were under NERICA 10 and NERICA 1 rice during 2024 and 2025. The IERs that were less than unity implied that the intercrops were economically inferior, even if a yield advantage existed. The intercropping systems showed LER>1 but IER <1. This signifies that the biological efficiency is high, especially for intercropped NamChe 5, NamChe 3 and NERICA 4 rice, but the low market prices or poor performance of a high-value crop could have reduced the income, reflecting sole cropping as more profitable. This is common in cereal-legume systems when legume prices are unstable.

4.5.3.7 Aggressivity

All the aggressivity (A) indices were less than unity, and the difference between the aggressivity of rice (Ab) as a base crop and legumes intercrops (Ai) was all negative. This implied that soybeans dominated rice in the intercropping combinations. Aggressivity often correlates with architectural dominance (height, light interception). High magnitude of aggressivity shown by soybean in NamChe 5 indicated strong competition with strong dominance or suppression by soybean as evidenced by a pLER above unity of 1.02. This was followed by moderate competition and noticeable competition by soybeans in NERICA 1 and NERICA 4 during 2024 and 2025. The lower A by soybean in NamChe 3 and NERICA 10 rice indicate that the soybean component maintained the rice yield stability as a base crop with minimal yield penalties on rice. It may also be implied that the soybean under NamChe 3 and NERICA 10 used different resources for Nitrogen by different rooting depth or slower growth rates. This improves resource-use efficiency. A weakly aggressive legume (soybean) could have relied more on N fixation instead of soil N. The low A lowers the risk of severe yield suppression of either crop or system failure under stress/ drought. Based on the findings under the current study, the component soybean with low A as a component crop with NamChe 3 and NERICA 10 rice may not have supplied enough complementary benefits. Early growth stages are critical for cereals, and the soybean may have competed for nutrients (N) or water early due to root overlap early in the season with the early maturing NERICA 10 and fast-growing Namche 3 rice. These interactions are not fully expressed in aggressivity calculations. Besides, A measures relative and not absolute yield and therefore, both component crops may have low yields. Similarly, NERICA1. NERICA 4 and NamChe 5 rice may be poorly adapted to intercropping and sensitive to mild competition.

5. Conclusion and Recommendations

NamChe 3 or NamChe 5 intercropped with Maksoy 4 gave high land equivalent ratios, land equivalent coefficients, rice equivalent yield, monetary advantage indices, income equivalent ratios, pooled yield and total rice grain yield equivalent values. The treatments thus recorded high economic performance and superior economic returns. This was coupled with moderate aggressivity, balanced competitive ratio and competitive indices with very low partial yield differences that gave a conducive intercropping environment, and demonstrated that the two rice-soybean intercropping systems had strong complementarity and thereby, identified as biologically and economically advantageous. The results highlight the recommendation of rice-soybean intercropping as a sustainable strategy for maximizing land productivity and farmer income under upland production conditions using NamChe 3 + Maksoy 4 and NamChe 5 + Maksoy 4 rice intercropping ecosystems.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during writing or editing of this manuscript.

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Competing Interests

Authors have declared that no competing interests exist.

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