Jurnal Kultivasi Vol. 25 (1) April 2026
ISSN: 1412-4718, eISSN: 2581-138x

Sevirasari N · Hidayati W · Az-Zahroh Z · Febriansyah B · Fiana MA · Rochmaniah NN · Faozi K · Bayyinah LN · Maryanto J · Fauzi A

Growth response and yield performance of upland rice intercropped with legumes

Abstract. Intercropping patterns in upland rice must be carefully managed to prevent excessive competition among crops. This research aimed to determine the ideal proportion of upland rice–legume intercropped and legume types for rice growth and yield. The research was conducted in Mersi, East Purwokerto, Banyumas, Central Java, from April–August 2025. The study was arranged in a split-plot design consisting of a main factor in form of the proportion of upland rice to legumes (1:1, 2:1, and 3:1), and a sub-factor, i.e., legume types (peanuts, mung beans, and soybeans). The data were analyzed using Analysis of Variance and Tukey's HSD test at $\alpha = 5\%$. The results showed that the height of upland rice plants in intercropping was significantly higher than in sole cropping at 35 and 56 days after planting (DAP). The SPAD leaf greenness index of upland rice leaves at 70 DAP in sole cropping was significantly higher than in intercropping. Intercropping produced the insignificant number of stems, leaves, panicles, dry weight, number, and weight of grain per plant as upland rice in sole cropping. The number and weight of empty grains per plant, as well as upland rice productivity in sole cropping, were significantly higher than in intercropping. Both factors did not significantly affect the growth and yield of upland rice under intercropping condition. Intercropping upland rice and peanuts at a 2:1 planting proportion resulted in a land equivalent ratio greater than 1, indicating that the system was productive and efficient despite a high competitive ratio.

Keywords: Competitive ratio · Land equivalent ratio · Legume types · Peanuts · Upland rice productivity

Submitted: 21 October 2025, Accepted: 27 April 2026, Published: 30 April 2026
DOI: https://doi.org/10.24198/kultivasi.v25i1.67508

Sevirasari N* · Hidayati W[1] · Az-Zahroh Z[2] · Febriansyah B[1] · Fiana MA[1] · Rochmaniah NN[1] · Faozi K[1] · Bayyinah LN[1] · Maryanto J[3] · Fauzi A[4]
[1] Agronomy and Horticulture Laboratory, Department of Agrotechnology, Faculty of Agriculture, Jenderal Soedirman University. Jl. Dr. Soeparno 61 Karangwangkal, Purwokerto 53123, Central Java, Indonesia
[2] Plant Breeding and Biotechnology Laboratory, Department of Agrotechnology, Faculty of Agriculture, Jenderal Soedirman University. Jl. Dr. Soeparno 61 Karangwangkal, Purwokerto 53123, Central Java, Indonesia
[3] Soil science laboratory, Department of Agrotechnology, Faculty of Agriculture, Jenderal Soedirman University. Jl. Dr. Soeparno 61 Karangwangkal, Purwokerto 53123, Central Java, Indonesia
[4] Agroecology laboratory, Department of Agrotechnology, Faculty of Agriculture, Jenderal Soedirman University. Jl. Dr. Soeparno 61 Karangwangkal, Purwokerto 53123, Central Java, Indonesia
*Correspondence: nindy.sevirasari@unsoed.ac.id

Sevirasari N, Hidayati W, Az-Zahroh Z, Febriansyah B , Fiana MA, Rochmaniah NN, Faozi K, Bayyinah LN, Maryanto J, Fauzi A. 2026. Growth response and yield performance of upland rice intercropped with legumes. Jurnal Kultivasi, 25 (1): 11-27.

Introduction

Upland has great potential to be developed and its productivity increased through agricultural activities, supported by the increasing demand for food in Indonesia, which continues to increase (Benu et al., 2023). The use of upland in agriculture plays a role in helping to increase national food production, one of which is through the planting of upland rice. Upland rice cultivation through the Integrated Crop Management approach is an approach to rice cultivation that is efficient in the use of inputs and pays attention to the wise use of natural resources with the aim of increasing productivity and farmer income, as well as maintaining the sustainability of the production environment through the integrated management of land, water, plants, plant pests, and climate (Rambe et al., 2024).

Upland areas where upland rice is cultivated generally have limited water and low soil fertility (Jarrar et al., 2023). It is known that over the past 5 years (2018–2022), the average rainfall in Banyumas Regency has decreased, especially in July and August during the dry season, from an average of 80 mm to 54 mm (Peraturan Daerah Kabupaten Banyumas Nomor 12 Tahun 2024, 2024). This will affect water availability in uplands that rely solely on rainwater. Uplands generally have low organic matter content with high soil acidity (acidic pH) (Winazira et al., 2021). One approach to increasing upland productivity is the implementation of soil conservation practices (Heryani & Rejekiningrum, 2020). Biological soil conservation can be carried out through cover crop planting methods and intercropping patterns (Bukovsky-Reyes et al., 2019; Pokharel et al., 2023). Intercropping is a method of planting two or more different types of crops on the same land for mutual benefit (Beets, 2019). Crop intensification occurs in both temporal and spatial dimensions when two or more crops are grown concurrently on the same field (Andrews & Kassam, 1976). In dry farming conditions, intercropping systems are typically low-input and risk-reducing for crop diversification and meeting subsistence goals (Nandhini & Somasundaram, 2020).

The potential for upland rice in Banyumas Regency is quite promising for development in 10 subdistricts, namely Wangon, Rawalo, Kebasen, Somagede, Kalibagor, Banyumas, Ajibarang, Gumelar, Pekuncen, and Kedungbanteng. Spatially, Banyumas has zones that are relatively suitable for the development of upland rice, particularly in sub-districts dominated by dryland or transitional rice-fallow agroecosystems (Saraswati et al., 2006). Data from the Banyumas Central Statistics Agency (BPS) for 2023 shows that the area of upland rice fields was 202 hectares, with a production of 893.24 tons and an average yield of 4.42 tons per hectare. Harvesting is concentrated in Lumbir (68 ha; 302.60 tons), Wangon (14 ha; 60.90 tons), Kebasen (29 ha; 130.00 tons), Kalibagor (84 ha; 369.60 tons), and Ajibarang (7 ha; 30.14 tons) (BPS, 2023).

From an agronomic perspective, Banyumas Regency is well-suited for developing rice–legume intercropping, as the combination of suitable land, rainfall patterns, and a large rice production base makes this system more viable than continuing to rely on rice sole cropping. Banyumas Regency also has a strong legume base, so intercropping can utilize crops that farmers are already familiar with. A study on upland rice farming in Ajibarang indicates that approximately 70% of the area consists of upland fields, and that upland rice cultivation on these fields is economically viable, with a benefit-cost ratio of 1.36 (Saraswati et al., 2006). Legume cultivation in Banyumas Regency is widespread and continues to expand, as evidenced by official data on harvested area and production for 2023 for soybeans, mung beans, and peanuts, as well as by the results of a study on priority commodities that identifies several legumes as potential or priority crops in a number of subdistricts in Banyumas (BPS Kabupaten Banyumas, 2026; Destiningsih, 2016).

Among the existing intercropping systems, cereal-legume intercropping is an important and profitable combination because this system has a high potential to reduce inputs such as fertilizers, improve environmental quality, and reduce nutrient emissions, especially in developing countries, where the use of fertilizer inputs and high nutrient emissions in the atmosphere (Raza et al., 2020). Intercropping with legumes increases the accumulation of nutrients, especially nitrogen, plant growth, and crop yields Raza *et al.* (2023). Intercropping with legumes increases the growth and yield components of red rice during irrigation water shortage conditions (Arifuddin et al., 2019).

Setting the proportion of plants is important to know whether the model in the cropping system used is profitable compared to sole cropping, and minimizes competition for space and light distribution (Feng et al., 2019) between upland rice and legume plants. Intercropping rice with legumes can minimize the impact of pest and disease attacks compared to the use of chemical pesticides Iwuagwu *et al.* (2019). According to Assefa & Bitew (2023), the ideal intercropping proportion of lowland rice–uci beans (*Lathyrus sativus* L.) is 3 : 1, with a maximum rice production efficiency of 5.1 tons/ha. The proportion of 75% rice and 25% soybeans produces a higher land equivalent coefficient and area time equivalent ratio compared to the proportion of 50% : 50% (Ozioma et al., 2024).

Legumes are planted after upland rice so that the shade does not hinder the early growth of rice, and by the time the legumes grow, the rice is already tall enough (Galo, 2025). The rice root system is already strong enough, and competition for light and nutrients can be controlled (Papong & Cagasan, 2020), and the efficiency of space and light utilization becomes more optimal (Assefa & Bitew, 2023). Legumes were intercropped after the upland rice plants were 3 weeks after planting (WAP) (Arifuddin et al., 2019). Upland rice intercropped with *C. breviflora,* where beans are planted 25 days after rice is planted, does not hinder the growth and yield of rice (Meirelles et al., 2024).

Intercropping performance is strongly influenced by relative planting density, temporal niche differentiation, and relative height differences among plants; that is, the biological effects of planting proportions may depend on the companion plants' species identity (Ruillé & Beillouin, 2026). This study focuses on the ability to detect differences among legume species and how these species modify the effects of proportions. Intercropping optimization is strongly influenced by species combinations, crop ratios, and sowing densities; therefore, the selection of levels for the legume species factor must be based on the agronomic and ecological differences among species (Zustovi et al., 2024). Based on this, the selection of peanuts, mung beans, and soybeans as sub-plot levels is justified because all three represent three different types of legumes in terms of root architecture, drought stress tolerance, growth duration, water requirements during the generative phase, and potential contribution to system complementarity (Afonso et al., 2025). Peanuts were selected because they are more drought-tolerant, have a strong root system, and can explore the soil effectively, thereby potentially enhancing complementarity with upland rice (Gelaye et al., 2025). Mung beans were selected because they have a short growth period and possess drought escape mechanisms, although they remain sensitive during the flowering and pod-filling stages (Singh et al., 2021). Soybeans were selected because they have higher water requirements and are more sensitive to drought stress, particularly during the reproductive stage, thus representing legumes with greater resource demands (Wang et al., 2022). This study aims to determine the optimal intercropping proportion between upland rice and legumes, as well as the most suitable legume species (peanuts, mung beans, and soybeans), to improve rice growth and yield, thereby generating appropriate technology that can be adopted by farmers.

Materials and Methods

Study area. This study was conducted from April to August 2025 in the experimental field, Mersi, East Puswokerto, Banyumas Regency, Central Java Province, Indonesia, located at 7°25′51″S, 109°16′1″E, and an altitude of ±80.9 m above sea level (asl). Morphological and post-harvest analysis were conducted in the Agronomy and Horticulture Laboratory, Faculty of Agriculture, Jenderal Soedirman University.

Experimental design. This research aimed to determine the ideal proportion of upland rice intercropped with legume and legume types for rice growth and yield. The materials used were Situ Bagendit upland rice variety, mung beans (VIMA 5), peanuts (Lurik), and soybeans (Grobogan), Arbuscular Mycorrhizal Fungi, Legume Inoculant, Urea fertilizer (N: 46%, Kaltim), SP-36 (P_2O_5: 36%, S: 5%, PETRO) fertilizer, KCl (K_2O: 60%, PETRO), herbicides post-emergent, insecticide, fungicide, and dolomite.

The research was arranged by a split-plot experimental design with two treatment factors and three blocks as replicates. The main factor was the proportion of upland rice rows to legume rows, consisting of three levels: 1:1, 2:1, and 3:1 rows. The sub-plots were planting patterns consisting of 3 levels: rice + peanuts, rice + mung beans, rice + soybeans. Sole cropping patterns of rice, peanuts, mung beans, and soybeans served as controls. Each experimental plot unit covers an area of 4 m^2 (2 m x 2 m), with a planting distance of 25 cm x 25 cm for rice (Paiman et al., 2023) and a row spacing of 40 cm x 15 cm for peanuts (Hawalid, 2019) and mung beans (Amanullah et al., 2022), and 40 cm x 20 cm for soybeans (Harsono et al., 2021). In intercropping, the distance between legumes is adjusted according to the proportion being tested, while the distance within rows is the same as the distance within rows in sole cropping, to reduce competition between the two plant species.

There were 9 treatment combinations and 4 control treatments. The total land area was 156 m^2 (4 m^2 x 9 units x 3 blocks + 4 control units x 3 blocks). One experimental plot unit contained 64 rice plants, and the experimental units with a ratio of upland rice to legumes of 1:1 contained 91 peanut and mung bean plants, and 70 soybean plants. The ratio of upland rice to legumes was 2:1, with 52 peanuts and mung beans, and 40 soybeans. The ratio of upland rice to legumes was 3:1, with 39 peanuts and mung beans, and 30 soybeans. The peanut and mung bean sole cropping population was 65 plants, and the soybean sole cropping population was 50 plants. A schematic of the cropping model could be seen in Figure 1.

Figure 1. Model of the proportion of intercropping of legume rows : rice (a) 1: 1, (b) 1: 2, (c) 1: 3. Rice planting distance 25 cm x 25 cm.

Research procedure. The research site was a taro field (*Colocasia esculenta*). The soil was thoroughly plowed to loosen and rid the soil of weeds. Experimental plot units were made with a size of 2 m (length) x 2 m (width) for 27 experimental plot units for intercropped and 12 experimental plot units for sole cropping. Rice seeds were sown (soil + 500 g arbuscular mycorrhizal fungi) for 21 days, then transplanted to the cultivated land (Akanvou et al., 2007). Legumes (peanuts, mung beans, soybeans) were intercropped after the upland rice plants were 3 weeks after planting (WAP) (Arifuddin et al., 2019). Before planting, legumes were coated with 10 g/kg legin (Arifuddin et al., 2019). Legin (Legume Inoculant) is a biofertilizer in the form of an inoculant containing *Rhizobium* bacteria designed to colonize the roots of leguminous plants. Irrigation was carried out every 2–3 days according to weather conditions. Seedling of rice and legumes was transplanted by immersing 2 seeds in each planting hole.

SP-36 fertilizer 75 kg.ha^{-1} (36% P_2O_5, 5% S) and KCl 50 kg.ha^{-1} (60% K_2O) have been given 3 days before planting, a urea fertilizer dose of 200 kg.ha^{-1} (46% N) was given when the rice plant was 7 and 21 Days After Planting (DAP) or before flowering, with each ½ dose, namely 100 kg.ha^{-1} (46 kg N.ha^{-1}) by being buried between rows of plants (rows). Base fertilizer has been given when transplanting legumes with a dose of 25 kg.ha^{-1} Urea + 100 kg.ha^{-1} SP-36 (2/3 dose) + 100 kg.ha^{-1} KCl (2/3 dose) (IP2TP, 2000). When the legume plants were 4 weeks (28 Days After Sowing), follow-up fertilizer was given as much as 25 kg.ha^{-1} Urea + 100 kg.ha^{-1} SP-36 (1/3 dose) + 100 kg.ha^{-1} KCl (1/3 dose) by burying it between rows of plants (rows) 5 cm from the planting hole. Dolomite has been given at a dose of 400 kg.ha^{-1} when the legume plant is 1 WAP and 3 WAP (each ½ dose by burying it in the hole at a distance of 7 cm from the planting hole. Upland rice was harvested after 13 WAP, and legume was harvested after 11 WAP for mung beans and soybeans, 12 WAP for peanuts. Depending on plant conditions, the intercropping of upland rice with legumes on the same land lasted for ±10 weeks.

The number of samples used for each experimental unit was five plants. The research variables observed were plant growth components, plant yields, and the land use efficiency of intercropping systems compared to monocropping. Plant height (cm) was measured from the base of the plant to the tip of the tiller of the plant using a ruler at 35 and 56 DAP (Cavite et al., 2021). The number of tillers and the number of leaves were counted manually at 35 and 56 DAP by physically separating them and counting the number of tillers and the number of leaves on each plant, ensuring that each plant was a separate unit. SPAD lead greenness index was measured at 70 DAP using a portable chlorophyll meter that inserts a leaf into a sensor at the midpoint of the topmost fully developed leaf, and 5 representative plants were randomly selected for the measurements in each experimental unit (Yue et al., 2020). Dry weight of roots, dry weight of shoots, and total dry weight (g.plant^{-1}) were oven dried at 80 °C until they reached a constant weight, then the dry weight was measured using a digital scale at 56 DAP. The number of filled grains and the number of empty grains per plant were calculated at harvest time using a seed counter. The weight of filled grains and the weight of empty grains were calculated based on the dry grain weight at harvest. Rice productivity was measured as yield per hectare (q.ha^{-1}), calculated from the total harvested rice grain for a given area (Gollin & Udry, 2021).

Because intercropping systems are diverse and complex, evaluation is challenging (Khanal et al., 2021). Land equivalent ratio (LER) is the land area required by crops in a sole cropping system to produce the same yield as crops in a dual cropping system, compared to the land area required by component crops to produce the same yield for sole cropping (Karunarathna & Maduwanthi, 2022). Crop biomass yield per unit area is typically used to calculate the land equivalent ratio (LER), which is a commonly used indicator of the yield advantage of multi-crop farms over monocropping (Deb & Dutta, 2022). A multifunctional LER_M that uses LER_P for provisioning and LER_R for regulating services. The productivity LERP component was determined using the following method for systems with only two components, as simulated here (Khasanah et al., 2020). A LER of more than 1.0 indicates a positive intercropping advantage and higher interspecific facilitation compared to interspecific competition. The land equivalent ratio can be calculated by using the following formula.

$$LER = LER\ a + LER\ b = \frac{Y_{ab}}{Y_{aa}} + \frac{Y_{ba}}{Y_{bb}}$$

Where Yab (the yields of rice in intercropped rice–legumes) and Yba (the yields of legumes intercropped with rice–legumes) were the LER of two components in intercropping, and Yaa and Ybb were those in sole cropping of rice and sole cropping legumes, respectively.

The Competitive Ratio (CR) is an index used to indicate the degree of dominance or relative competitiveness of one species over another in an intercropping system; the higher a plant's CR value, the stronger its competitiveness compared to its companion plant (Willey & Rao, 1980). The competitiveness ratio is a better measure of plant competitiveness than relative crowding coefficient (k) and aggressivity level (A) (Karunarathna & Maduwanthi, 2022). The Competitive ratio can be calculated by using the following formula.

$$CRa = \left(\frac{LER_a}{LER_b}\right) x \left(\frac{Z_{ba}}{Z_{ab}}\right)$$

$$CRb = \left(\frac{LER_b}{LER_a}\right) x \left(\frac{Z_{ab}}{Z_{ba}}\right)$$

Where LERa (Land Equivalent Ratio of rice), LERb (Land Equivalent Ratio of legumes, Z (sown proportion of rice in intercropping), Z (sown proportion of legumes in intercropping). Crops can be grown in association if the Cra value is less than 1. The opposite is matching crop b.

Data Analysis. Compiled data was analyzed using analysis of variance (ANOVA), followed by the Post Hoc Tukey's HSD (honestly significant difference) Test at the α level of 5%. A t-test analysis was used to determine the difference between the means of cropping patterns: intercropping and sole cropping (Mishra et al., 2019). The statistical analysis was performed using Rstudio and Microsoft Excel.

Results and Discussion

Rainfall distribution. The rainfall situation of tested location was depictd in Figure 2, with the monthly rainfall (mm) from April to August 2025 is 306, 325, 122, 44, and 44 mm, respectively. Based on those rainfall distribution, the study area has two consecutive wet months (April–May) followed by one humid month (June) and two dry months (July–August), so according to Oldeman's classification, it is classified as climate type D2. This is also supported by data from the past 30 years (1991–2021) and 5 years (2018–2022) in the Banyumas Regency Regional Regulation. Climate type D2 is suitable for one planting of paddy or one palawija crop, depending on the supply of irrigation water (Aldiansyah & Risna, 2023; Oldeman, 1980). The study area is classified as Oldeman D2 and is suitable and relevant for the application of rice–legume intercropping. Water availability during the study was sufficient for the vegetative phase, but there was a deficit in the final phase. This risk can be mitigated by selecting the right planting time and applying intercropping with drought-tolerant legumes (Khatun et al., 2021).

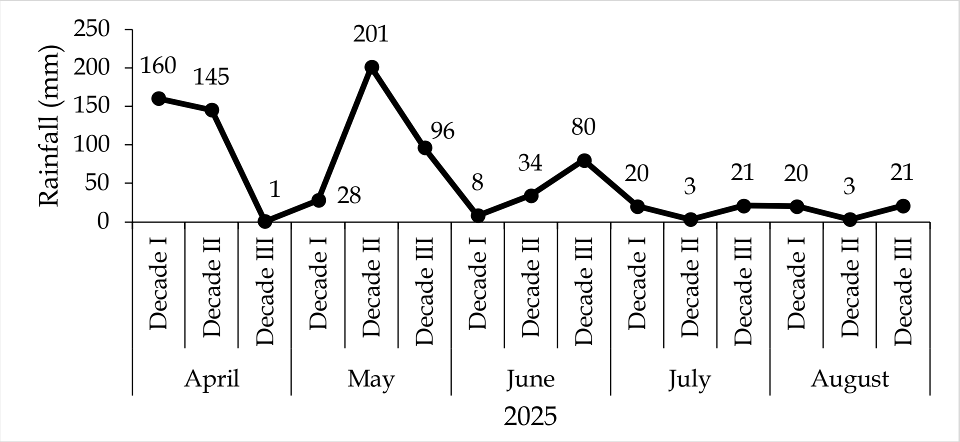

Figure 2. Rainfall distribution at the research site from April to August 2025 (BPSB, 2025)

Cereal–legume intercropping increases biomass, yield per unit area, and has a land equivalent ratio (LER) >1, with a progressively more pronounced yield advantage over sole cropping under conditions of progressive drought (Wang et al., 2026). This is particularly relevant for D2, as its rainfall pattern is not as consistent as that of wetter regions; therefore, a system that is more resilient to rainfall fluctuations will be more secure both agronomically and economically (Liu et al., 2025). Drought-tolerant legumes included peanuts, mung beans, and soybeans. Peanuts and mung beans are classified as drought-tolerant legumes, with peanuts having the highest level of tolerance, soybeans are classified as legumes with lower drought tolerance, especially in the generative phase, making them less adaptive to limited water availability compared to the other two legumes (Luo & Lin, 2025). The planting time for upland rice was the third week of April, and it was harvested in the fourth week of July. Legumes were planted in the second week of May and harvested in the fourth week of July (green beans and soybeans) and the first week of August (peanuts).

Plant height and number of tillers. The ability of a species to compete for light is significantly influenced by plant height, which is a central component of the plant's ecological strategy. Additionally, plant height is strongly correlated with life span, seed mass, and time to maturity, above-ground biomass, plant fitness, and leaf photosynthesis (Wang et al., 2019). There was no interaction effect on plant height among the treatment factors tested. The result showed that the plant height of upland rice in intercropping was significantly higher than in sole cropping at 35 and 56 days after planting (DAP) of 60.58 cm and 77.18 cm, respectively (Table 1). This may be due to the symbiosis that occurs between legumes that can fix N with rice. Plants can release root exudates, and organic compounds become signals that attract microorganisms to approach them so that they form a symbiotic relationship (plants – rhizosphere bacteria–plants). Root exudates usually create a nutrient-rich rhizosphere micro-environment, where microbial activity is stimulated. Root exudates consist of various primary and secondary compounds, including carbohydrates, amino acids, organic acids, phenolics, flavonoids, and auxins (Wu et al., 2023). However, the treatment of intercropping proportions and the type of legume used did not significantly affect plant height (Table 1).

The tiller number per unit area is a critical agronomic factor in determining yield. Consequently, real-time methods involving manual counting are considered a precise and efficient method for obtaining the tiller number in field conditions can be beneficial in establishing a reasonable group density (Fang et al., 2020). There was no interaction effect on the number of tillers per plant among the treatment factors tested. The variable number of tillers per clump was not affected by the treatment of intercropping proportions, type of legume, or planting pattern used. This may be due to the vegetative phase of tillering being influenced by factors such as light, temperature (Wang et al., 2024), and the application of nitrogen fertilizer (Kalaitzidis et al., 2025), which, in this case, both in intercropping and sole cropping treatments, all received the same fertilizer treatment. According to the results (Table 1), the number of tillers per plant at 56 DAP reached 27.07 for intercropping and 27.83 for sole cropping, while according to the results of the study (Idaryani et al., 2017), the number of tillers reached 20.12 at harvest. According to the variety description, the number of productive tillers of Situ Badegendit upland rice was 12–13 stems per clump (Simanulang, 2008). The proportion of rice-legume and the types of legume did not inhibit the growth of rice intercropped at 35 and 56 DAP. Rice habitus in the period 35–56 DAP has not had much influence or competition with the legume. It has different nutrient requirements, so there is no difference in the intercropping or sole cropping system.

Number of leaves, number of panicles, and SPAD leaf greenness. The leaf is the organ that is essential for the production of nutrients and photosynthesis in plants. Consequently, the quantity of leaves is one of the primary indicators used to describe the development and growth of a canopy, flowering time, and yield potential (Lu et al., 2021). The number of panicles per plant is the main trait that determines the grain yield in rice (Gunasekaran et al., 2023). There was no interaction effect on the number of leaves and number of panicles among the treatment factors tested. The number of leaves and panicles was not affected by the intercropping proportion, legume type, and cropping system used (Table 2). This may be because during the 35–56 DAP, the main rice crop was not yet competing for light and water with the intercropping (legume) crop. Rice panicles generally begin to form at 40–45 days (panicle initiation) and then continue to develop until the panicles emerge and enter the flowering stage at 50–55 days. The number of tillers formed is an important stage in determining the number of panicles (Wang et al., 2024). The number of tillers (Table 1) and the number of panicles (Table 2) are both the same and do not significantly affect the treatment given. The more tillers that form, the greater the chance of producing offspring that will yield panicles. The number of panicles of 56 DAP Situ Bagendit upland rice was 16.12 in intercropping and 11.67 in sole cropping, as indicated by the data (Table 2). Meanwhile, according to the results of the study (Aziz et al., 2010), the number of panicles reached 37.2 at harvest. The number of productive tillers is part of the number of panicles per clump. The number of panicles per clump is one of the most decisive factors in determining yield, because the more panicles produced per clump, the greater the amount of grain produced, thereby increasing the potential for higher yields (Sution & Nurdin, 2015).

Table 1. Plant height and number of tillers at 35 and 56 DAP as affected by different proportions of upland rice intercropped with various legume types

Treatments	Plant height (cm)		Number of tillers per plant	
	35 DAP	56 DAP	35 DAP	56 DAP
Cropping patterns				
Intercropping	60.58 a	77.18 a	23.87 a	27.07 a
Sole cropping	55.97 b	72.39 b	21.17 a	27.83 a
Intercropped Rice-Legume Proportion				
1:1	61.68 a	76.35 a	24.20 a	27.91 a
2:1	60.78 a	78.06 a	24.33 a	27.16 a
3:1	59.28 a	77.12 a	23.07 a	26.13 a
CV (%)	7.71	3.02	14.93	15.86
Types of Legumes				
Peanuts	61.49 a	76.89 a	24.80 a	27.67 a
Mung beans	59.88 a	77.17 a	22.38 a	24.80 a
Soybeans	60.37 a	77.47 a	24.42 a	28.73 a
CV (%)	5.21	4.46	14.09	14.44
Interaction	-	-	-	-

Note: DAP (Days After Planting), (-) no interaction, CV (Coefficient of Variance). Cropping patterns were analyzed using the t-test. The average number of rice-legume intercropping followed by the same letter in each column indicates no significant difference in the Tukey HSD test at α = 95%.

Table 2. Number of leaves, number of panicles, and SPAD leaf greenness as affected by different proportions of upland rice intercropped with various legume types

Treatment	Number of leaves		Number of panicles*	SPAD leaf greenness index
	35 DAP	56 DAP	56 DAP	70 DAP
Cropping patterns				
Intercropping	86.10 a	112.30 a	16.12 a	38.39 b
Sole cropping	73.92 a	120.67 a	11.67 a	40.83 a
Intercropped Rice-Legume Proportion				
1:1	88.47 a	116.51 a	15.70 a	38.36 a
2:1	87.60 a	113.87 a	15.11 a	38.32 a
3:1	82.22 a	106.51 a	17.56 a	38.50 a
CV (%)	12.29	17.91	35,82	3.41
Types of Legumes				
Peanuts	89.47 a	115.09 a	16 a	38.06 a
Mung beans	79.53 a	104.22 a	16.93 a	38.15 a
Soybeans	89.29 a	117.58 a	15.44 a	38.96 a
CV (%)	12.96	16.24	27.72	3.58
Interaction	-	-	-	-

Note: DAP (Days After Planting), (-) no interaction, CV (Coefficient of Variance). Cropping patterns were analyzed using the t-test. The average number of rice-legume intercropping followed by the same letter in each column indicates no significant difference in the Tukey HSD test at α = 95%.

The soil and plant analyzer development (SPAD) value is an important indicator affecting rice yield and quality. The SPAD leaf greenness index is frequently used to describe a plant's concentration of nitrogen or chlorophyll (Zhang et al., 2024). There was no interaction effect on SPAD leaf greenness index among the treatment factors tested. The greenness index variable of SPAD upland rice leaves at 70 DAP in the sole cropping system is significantly higher than in the intercropping system (Table 2). The greenness of the leaves is closely related to the chlorophyll content in a plant tissue (Yue et al., 2025). Chlorophyll formation is very dependent on the availability of nitrogen, where the addition of nitrogen to a certain level will be followed by an increase in chlorophyll concentration (Elsayed et al., 2023). Fertilizer applied to sole cropping land is more focused on being absorbed by rice, while in intercropping land, the nutrients are divided for the needs of two plants (rice and legumes) with a denser plant population. In addition, rice aged at 70 DAP, the legume intercropped plants have begun to enter the maximum vegetative phase, which indicates that the plants need more nutrients to prepare for flowering. In intercropping, legumes supply nitrogen to other plants through direct transfer via root systems, tilling into the soil, the breakdown of their roots, and nitrogen transfer facilitated by plant-associated mycorrhizae (Thilakarathna et al., 2016). This happens all during the growing season, but when the legume is cut off and the plant matter decomposes, a large quantity of nitrogen is released into the soil, allowing nearby crops to use it. Additionally, nitrogen from the decomposition of legume residues can be used to restore soil fertility; this primarily depends on how the residues are used-burned, completely removed from the field, or incorporated, which is more beneficial (Kebede, 2021). Although legumes can fix nitrogen, this process is more beneficial for subsequent crops rather than directly for the rice that is currently growing. Therefore, chlorophyll content (as reflected by SPAD) is higher in sole croppings.

Root dry weight, shoot dry weight, and total dry weight of rice. An irreversible increase in size, plant growth is commonly referred to as net primary production (Hilty et al., 2021). Dry weight is measured when the amount of plant material has been dried to a constant moisture content (Turnage, 2022). The results of the study showed that the intercropping system produced root dry weight, shoot dry weight, and total dry weight of rice that were not significantly different from those of upland rice in a sole cropping system (Table 3). There was no interaction effect on the root dry weight, shoot dry weight, and total dry weight of rice among the treatment factors tested. Higher biomass values were a good indicator of the plant's potential to produce large yields of grain (Xi et al., 2024). There were no differences between sole cropping and intercropping treatments at various proportions and types of legumes, indicating that the main rice crop can adapt to normal conditions as well as in dense populations. The root systems of rice and legumes differ in depth, so root complementarity likely reduced direct competition for belowground resources (Homulle et al., 2022). As a result, total biomass accumulation remains comparable. Based on the total dry weight data of rice (Table 3), the total dry weight of intercropped rice was 42.51 g.plant^{-1}, while that of sole cropping was 36.36 g.plant^{-1}. According to Meirelles et al. (2024), without influencing grain yield, upland rice interplanted with *C. breviflora* (legume) demonstrated a greater overall dry mass production than sole rice.

Number of filled grains, number of empty grains, weight of filled grains, weight of empty grains, and productivity of rice. The yield components of rice are the number of filled grains, the number of empty grains, the weight of filled grains, weight of empty grains. A mature rice grain that is full of nutrients and fully developed as a result of the grain filling stage is called a filled grain (Kumar et al., 2020). The endosperm, the primary component of the grain, is where proteins, lipids, and carbohydrates are created and accumulated during this process, affecting the grain's weight, yield, and quality (Xu et al., 2021). There was no interaction effect on the number of filled grains, number of empty grains, weight of filled grains, weight of empty grains, and productivity of rice among the treatment factors tested. The study showed that the number of filled grains and the weight of filled grains did not significantly affect the treatment of intercropping proportion, legume type, and cropping system used (Table 4). Meanwhile, the sole cropping treatment significantly affected the number of empty rice grains by 574.42 and in the intercropping system by 239.56. This further impacted the weight of empty grains, which was found to be significant in the sole cropping system (3.40 g.plant^{-1}) while in the intercropping system, it was 1.29 g.plant^{-1} (Table 4). This shows that in a sole cropping system with a relatively free planting area without competition, large amounts of grain were produced. However, the large number of empty grains found in the sole cropping system can be caused by the inability of the plants to fill the rice grains optimally. The rice spikelet may be successfully pollinated and fertile, but the grain filling was not optimal, so the resulting grain was not full (Parida et al., 2022).

Table 3. Root dry weight of roots, shoot dry weight, and total dry weight of rice plant as affected by different proportions of upland rice intercropped with various legume types

Treatment	Root dry weight (g.plant^{-1})*	Shoot weight (g.plant^{-1})*	Total dry weight (g.plant^{-1})*
	56 DAP	56 DAP	56 DAP
Cropping patterns			
Intercropping	5.17 a	36.96 a	42.51 a
Sole cropping	3.20 a	33.16 a	36.36 a
Intercropped Rice-Legume Proportion			
1:1	5.01 a	36.31 a	42.46 a
2:1	4.85 a	35.45 a	40.29 a
3:1	5.65 a	39.13 a	44.77 a
CV (%)	38.27	16.85	20.09
Types of Legumes			
Peanuts	5.07 a	37.46 a	42.53 a
Mung beans	5.64 a	39.94 a	45.07 a
Soybeans	4.79 a	33.48 a	39.92 a
CV (%)	21.48	13.19	13.21
Interaction	-	-	-

Note: DAP (Days After Planting), (-) no interaction, CV (Coefficient of Variance). Cropping patterns were analyzed using the t-test. The average number of rice-legume intercropping followed by the same letter in each column indicates no significant difference in the Tukey HSD test at α = 95%. (*) sign: the CV is the result of data transformation.

Table 4. Yield component of rice plant as affected by different proportions of upland rice intercropped with various legume types

Treatment	Number of filled grains (plant^{-1})*	Number of empty grains (plant^{-1})*	Weight of filled grains (g.plant^{-1})*	Weight of empty grains (g.plant^{-1})*	Productivity of Rice (q.ha^{-1})*
Cropping patterns					
Intercropping	155.14 a	239.56 b	3.34 a	1.29 b	6.54 b
Sole cropping	191.17 a	574.42 a	4.89 a	3.40 a	13.39 a
Intercropped Rice-Legume Proportion					
1:1	151.62 a	226.53 a	3.30 a	1.19 a	6.97 a
2:1	171.24 a	255.49 a	3.62 a	1.39 a	7.17 a
3:1	142.56 a	236.64 a	3.11 a	1.28 a	5.48 a
CV (%)	22.52	18.78	19.63	22.30	20.65
Types of Legumes					
Peanuts	160.56 a	218.16 a	3.42 a	1.12 a	6.57 a
Mung beans	137.18 a	240.09 a	2.84 a	1.35 a	6.65 a
Soybeans	167.69 a	260.42 a	3.76 a	1.38 a	6.39 a
CV (%)	28.74	19.83	32.79	20.02	21.89
Interaction	-	-	-	-	-

Note: (-) no interaction. Cropping patterns were analyzed using the t-test. The average number of rice-legume intercropping followed by the same letter in each column indicates no significant difference in the Tukey HSD test at α = 95%. (*) sign: the CV is the result of data transformation.

Yield per hectare or productivity is a variable measured based on the dry grain yield. Yield is an important agronomic variable that serves as an indicator of whether a superior variety will be accepted or adopted by farmers (Sution & Nurdin, 2015). In intercropping, competition for water and nutrients during the grain filling phase reduced rice productivity. However, the amount of empty grains was lower because assimilate distribution was more efficient for the grains that are formed (sink limitation). Sole cropping excels in total yield because all resources are focused solely on rice. The potential yield of a variety can only be achieved if it is planted in growing conditions that are suitable for that variety. Differences in weather, water management, and soil type result in varying yields. The use of superior varieties in efforts to increase production plays a very important role. In addition, the yield potential of a particular variety cannot be separated from its level of adaptation and stability in a given growing environment research (Idaryani et al., 2017).

Land Equivalent Ratio (LER) and Competitive Ratio. One of the key variables in assessing the effectiveness of an intercropping system is the land equivalent ratio (LER) value. The LER indicates how much sole cropping land is needed to produce the same amount of yield as 1 hectare of intercropped land. A LER value greater than 1 indicates that land productivity (intercropping) is more efficient than sole cropping; conversely, if the LER value <1, then productivity is low (Dharmawangsa et al., 2020). The results showed that the best total LER value was obtained with an intercropping proportion of 2:1, at 1.68, indicating that intercropping provided 68% greater benefits than sole cropping. The second-highest LER was a proportion of 1:1 (1.25), and the lowest was a proportion of 3:1 with an LER of 1.20 (Table 5). In addition, the best LER of legumes was obtained in intercropping with peanuts, with a LER value of 2.13, followed by soybeans (0.35), and the lowest was mung beans with an LER of 0.17. Peanuts were highly suitable for intercropping with upland rice, whereas soybeans and mung beans have an LER <1, meaning that these two types of legumes are not land-efficient. Intercropping systems with legumes not only offer increased productivity through commodity diversification but also have beneficial effects on soil texture, microbial diversity, water retention, plant growth, and crop yields (Kokkini et al., 2025).

LER is a derived variable, not a direct variable such as plant height or rice yield. LER combines two yield components (rice + legumes) simultaneously. Although there were no significant differences in rice yield among the treatments, the contribution of legumes can vary greatly. Based on the results

(Table 4), rice yields did not differ significantly among treatments, but legume LERs did differ, resulting a difference in total LER. LER is a system-level index of intercropping performance because it integrates the relative yields of both component species against their respective sole crops, thereby reflecting land-use efficiency and the net outcome of complementarity and competition within the system. Therefore, LER may show significant treatment differences even when individual component responses are not statistically significant (Mead & Willey, 1980).

Intercropping upland rice with legumes increased land efficiency, growth variables, and plant biomass, which were relatively comparable to sole cropping. However, pure upland rice yields (grain productivity) remain higher in sole cropping because there was no competition with legumes. Legumes serve a long-term function in soil fertility (N-fixation) and crop diversification, making this system suitable for upland areas at risk. The proportions of 1:1, 2:1, and 3:1 were still within a relatively narrow range. The highest total LER at a ratio of 2:1 reflects conditions where the benefits of intercropping (resource complementarity and nitrogen fixation) outweigh the disadvantages of competition. This ratio represents the optimum point between the dominance of upland rice as the main crop and the contribution of legumes as companion crops, especially in agroclimatic conditions with limited water availability.

The competitive ratio (CR) in intercropping indicates how much more competitive one plant component is than another (Willey & Rao, 1980). Intercropping evaluation indices, including competitive ratio, assess different aspects of intercropping system performance, and intercropping yields are influenced by total planting density as well as the proportion of crops in the intercropping system (Zustovi et al., 2024). Based on the crop proportion, all competitive ratios were greater than 1, indicating that both crops were actively competing. At a proportion of 2:1 and 3:1, the legume was more competitive than the upland rice; however, even when the legume was dominant, the intercropping system remained efficient (high LER). The competitive ratio varies with planting density, so the competitive ratio is also useful for evaluating the design of intercropping proportions or densities (Y. Wang et al., 2024).

Based on the competitive ratio (CR) and land equivalent ratio (LER) values, peanuts exhibit a very high level of competitiveness in an intercropping system with upland rice. Nevertheless, this combination yields the highest total LER value of 2.63; thus, it can be considered the most profitable and ideal combination for the implementation of intercropping. Conversely, for mung beans, a CR value <1 indicated that this crop was outcompeted by upland rice, and this condition aligns with the low LER value, the combination considered less suitable for intercropping systems. As for soybeans, the CR value indicates relatively more balanced competition; however, because the LER value was <1, the rice–soybean intercropping system is still considered less efficient in terms of land use. In intercropping, there is indeed competition for light, water, and nutrients, but at the same time, two species can also complement each other through differences in canopy height, root depth, nutrient uptake timing, or the ability of legumes to fix nitrogen (Neamatollahi et al., 2013). System efficiency often arises due to resource partitioning and facilitation, not because competition is eliminated. Therefore, even if one crop appears to be "dominant" in terms of CR, the system can still be more productive overall, resulting in an LER >1, indicating greater land-use efficiency (Wang et al., 2024).

Table 5. The land equivalent ratio and competitive ratio of intercropped rice-legume

Intercropped Rice-Legume	Land Equivalent Ratio			Competitive Ratio	
	Rice	Legume	Total	Rice	Legume
Intercropped Rice-Legume Proportion					
1:1	0.53	0.72	1.25	1.70	1.54
2:1	0.54	1.15	1.68	1.82	3.09
3:1	0.41	0.79	1.20	2.37	2.79
HSD (P≤0.05)	0.24	0.32	0.07	1.01	0.93
Types of Legumes					
Peanuts	0.50	2.13	2.63	1.82	5.22
Mung beans	0.50	0.17	0.67	2.94	0.47
Soybeans	0.48	0.35	0.83	1.13	1.74
HSD (P≤0.05)	0.19	0.73	0.63	0.66	1.11

Intercropping rice and peanuts were more productive than other legumes. LER data showed that peanuts contribute more than mung beans or soybeans. The weight of peanut seeds per plant in intercropping and sole cropping did not differ significantly (data unpublished). From rainfall data (Figure 2), it is known that during the generative phase of the plants, July and August were dry months, indicating drought. Peanuts were known as the most tolerant legume to limited water availability because they have a strong and deep tap-root system, relatively low transpiration rates, and the ability to adapt to light-textured soils (Zhen et al., 2024). These plants were still able to produced well in relatively low rainfall, with critical phases mainly during gynophore formation and pod filling (Dong et al., 2024).

Mung beans have moderate to high drought tolerance, mainly because of their short growing season, which allows them to complete their life cycle before water stress reaches severe levels (drought escape mechanism) (Wenham et al., 2019). However, mung beans remain sensitive to water deficits during the flowering and pod filling stages (Singh et al., 2021). Meanwhile, soybeans are the most drought-sensitive legume of the three, because their root system is relatively shallow and their water requirements are higher, especially during the generative phase (Wang et al., 2022). Water deficits during the flowering and seed filling phases in soybeans can cause significant yield losses, so this crop requires a more stable water supply than peanuts and mung beans (Aziez & Prasetyo, 2022).

There was no interaction between planting proportions and legume types was likely due to the high degree of niche complementarity between rice and legumes, both temporally and spatially. The absence of interaction between the two factors indicates that the system's response did not depend on specific treatment combinations. Legumes were planted 3 weeks after rice, so their resource-demand phases did not fully overlap. Furthermore, differences in root system characteristics and nutrient utilization patterns result in relatively low direct competition between crops. Consequently, interspecific interactions were relatively weak, and the growth and yield responses of upland rice remained consistent across different planting proportions and legume types.

The differences in proportions remained within a non-extreme range, so the system was not sufficiently disrupted to trigger interactions, and the variability among treatments was small (Zustovi et al., 2024). The selected legume species share the same ecological function, namely, nitrogen fixation (Kebede, 2021). Although the selected legume species differ in root architecture, drought response, and crop duration, these species-specific traits may not have been fully expressed under the present experimental conditions (Gelaye et al., 2025; Islam et al., 2021; Singh et al., 2021; X. Wang et al., 2022). Water availability was still adequate during the vegetative stage, the legumes were introduced three weeks after rice, and the tested planting proportions were within a relatively narrow range; therefore, interspecific competition remained limited, and treatment variability was small (Meirelles et al., 2024).

Despite the non-significant effects on rice yield components, the intercropping system of upland rice with peanut remains agronomically advantageous. This is evidenced by the high land equivalent ratio (LER), which reached 2.63 in the rice–peanut combination, indicating substantial land-use efficiency compared to monocropping. Similarly, the 2:1 planting proportion resulted in the highest LER (1.68), suggesting an optimal balance between rice dominance and legume contribution. Although the competitive ratio (CR) indicated that peanut was more dominant in resource utilization, this did not negatively affect the overall system performance; instead, it contributed to higher total land productivity. From a farmer's perspective, such dominance is acceptable as long as the combined yield and land efficiency increase. This interpretation is supported by recent studies showing that cereal–legume intercropping can stabilize yield and economic returns under variable rainfall, while farm-level analyses also demonstrate that legume–cereal intercropping can improve profitability through better land use and reduced input costs (Wang et al., 2026). In addition, peanut's greater adaptability to dry conditions, particularly under late-season water limitation, makes it a more reliable companion crop than mung bean or soybean. Importantly, rice growth and yield were not significantly reduced across treatments, indicating that intercropping provides additional output without compromising the main crop. Therefore, the adoption of upland rice–peanut intercropping can be justified not only by ecological complementarity but also by its capacity to enhance land-use efficiency, diversify production, and reduce farming risks under variable environmental conditions.

Conclusion

Differences in the proportion of upland rice–legume intercropping and legume types did not significantly affect the growth and yield of upland rice. However, rice–legume intercropping improved land-use efficiency, particularly at the 2:1 proportion with an LER >1 (1.68) and in the upland rice–peanut combination, which produced the highest LER >1 (2.63). Although the competitive ratio showed that some legumes, especially peanuts, were more competitive than rice, this dominance was not detrimental because the intercropping system still achieved an LER greater than 1. In contrast, the mung bean and soybean combinations were less efficient and are therefore not recommended.

Acknowledgments

The Authors gratefully acknowledge the 2025 BLU research grants by the Institute of Research and Community Service (LPPM) of Jenderal Soedirman University, under the Competency Enhancement Research (RPK) scheme and grant number (14.519/UN23.34/PT.01/V/2025).

References

Afonso P, Castro I, Couto P, Leal F, Carnide V, Rosa E, Carvalho M. 2025. Root Phenotyping : A Contribution to Understanding Drought Stress Resilience in Grain Legumes. *Agronomy*, *15*(4), 1–15.

Akanvou RK, Becker M, Bastiaans L, Kropff MJ. 2007. Morpho–physiological characteristics of Cover crops for analysis of upland rice production in relay intercropping systems. *Sciences & Nature*, *4*(2), 205–216.

Aldiansyah S, Risna. 2023. Mapping of oldeman agro-climatic zone based on climate hazards group infrared precipitation with station database in Southeast Sulawesi. *Ecotrophic*, *17*(2), 174–187.

Amanullah F, Ropalia, Lestari T. 2022. Budidaya kacang hijau ramah lingkungan. *Seminar Nasional Penelitian Dan Pengabdian Pada Masyarakat 2022*, 57–62.

Andrews DJ, Kassam AH. 1976. The Importance of Multiple Cropping in Increasing World Food Supplies. In *American Society of Agronomy* (Vol. 27). https://doi.org/10.2134/asaspecpub27.c1

Arifuddin A, Wangiyana W, Aryana I. 2019. Effect of relay-planting several legume species at various ages of rice on growth and yield of red rice grown together with legume crops under aerobic irrigation system. *International Journal of Environment, Agriculture and Biotechnology*, *4*(6), 1704–1710.

Assefa E, Bitew Y. 2023. Enhancing the land use efficiency of low-land rice (*Oryza sativa* L.)—Grass pea (*Lathyrus sativus* L.) additive series relay intercropping in North-Western Ethiopia: A farmer's indigenous knowledge. *PLoS ONE*, *18*(7 July), 1–17. https://doi.org/10.1371/journal.pone.0281410

Aziez AF, Prasetyo A. 2022. Root growth response of soybean (*Glycine max* L.) under water deficit. *Journal of Biodiversity and Biotechnology*, *2*(2), 63–69.

Aziz A, Basri AB, Nasir A, Pesireron M. 2010. Uji multilokasi 6 varietas padi gogo di Provinsi NAD. *Prosiding Seminar Nasional: Mewujudkan Kedaulatan Pangan Pada Lahan*, *27*, 338–345.

Beets WC. 2019. *Multiple cropping and tropical farming systems*. CRC Press.

Benu FL, Lawa Y, Neolaka YAB. 2023. Mini Review: Peran biofertilizer pada pertanian lahan kering. *Jurnal Beta Kimia*, *3*(1), 40–49. https://doi.org/10.35508/jbk.v3i1.11656

BPS. 2023. *Harvested Area, Production and Yield Rate of Dryland Paddy, 2023*. BPS Kabupaten Banyumas. https://banyumaskab.bps.go.id/id/statistics-table/1/NjM1IzE%3D/luas-panen-produksi-dan-rata-rata-produksi-padi-ladang-tahun-2023.html

BPS Kabupaten Banyumas. 2026. *Kabupaten Banyumas Dalam Angka 2026 Volume 51*. https://banyumaskab.bps.go.id/id/publication/2026/02/27/4e4f855322bf9f80022acafb/kabupaten-banyumas-dalam-angka-2026.html

Bukovsky-Reyes S, Isaac ME, Blesh J. 2019. Effects of intercropping and soil properties on root functional traits of cover crops. *Agriculture, Ecosystems and Environment*, *285*(106614), 1–10. https://doi.org/10.1016/j.agee.2019.106614

Cavite HJM, Mactal AG, Evangelista EV, Cruz JA. 2021. Growth and yield response of upland rice to application of plant growth-promoting rhizobacteria. *Journal of Plant Growth Regulation*, *40*(2), 494–508. https://doi.org/10.1007/s00344-020-10114-3

Deb D, Dutta S. 2022. The robustness of land equivalent ratio as a measure of yield advantage of multi-crop systems over monocultures. *Experimental Results*, *3*, 1–13. https://doi.org/10.1017/exp.2021.33

Destiningsih R. 2016. Analisis Komoditas Unggulan Pangan Kabupaten Banyumas. *Jurnal REP*, *1*(1), 35–48. https://doi.org/10.31002/rep.v1i1.51

Dharmawangsa L, Nujanah U, Pujiwati H, Setyowati N, Prasetyo P. 2020. Nilai kesetaraan lahan dan hasil jagung manis tumpangsari dengan kacang-kacangan di pertanian organik. *Seminar Nasional Lahan Suboptimal*, *1*, 224–236.

Dong J, Shen X, Li Q, Xue Z, Hou X, Miao H, Ning H. 2024. Irrigation and fertilization scheduling for peanut cultivation under mulched drip irrigation in a desert-oasis area. *Plants (Basel, Switzerland)*, *13*(1), 144. https://doi.org/10.3390/plants13010144

Elsayed S, El-Hendawy S, Elsherbiny O, Okasha AM, Elmetwalli AH, Elwakeel AE, Memon MS, Ibrahim MEM, Ibrahim HH. 2023. Estimating chlorophyll content, production, and quality of sugar beet under various nitrogen levels using machine learning models and novel spectral indices. *Agronomy*, *13*(11), 2743.

Fang Y. Qiu X, Guo T, Wang Y, Cheng T, Zhu Y, Chen Q, Cao W, Yao X, Niu Q, Hu Y, Gui L. 2020. An automatic method for counting wheat tiller number in the field with terrestrial LiDAR. *Plant Methods*, *16*(1), 1–14. https://doi.org/10.1186/s13007-020-00672-8

Feng, L, Raza MA, Chen Y, Khalid MH Bin, Meraj TA, Ahsan F, Fan Y, Du J, Wu X, Song C, Liu C, Bawa G, Zhang Z, Yuan S, Yang F,Yang W. 2019. Narrow-wide row planting pattern improves the light environment and seed yields of intercrop species in relay intercropping system. *PLoS ONE*, *14*(2), 1–19. https://doi.org/10.1371/journal.pone.0212885

Galo E. 2025. Performance of upland rice intercropped legumes and level of nitrogen fertilizer. *International Journal of Agriculture and Biosciences 2025*. *14*(4), 740–747.

Gelaye Y, Li J, Luo H. 2025. Journal of Genetic Engineering and Biotechnology Exploring the role of Peanut (Arachis hypogaea L .) root architecture in enhancing adaptation to climate change for sustainable agriculture and resilient crop production : A review. *Journal of Genetic Engineering and Biotechnology*, *23*(3), 1–12. https://doi.org/10.1016/j.jgeb.2025.100535

Gollin D, Udry C. 2021. Heterogeneity, measurement error, and misallocation: Evidence from african agriculture. *Journal of Political Economy*, *129*(1), 1–80. https://doi.org/10.1086/711369

Gunasekaran A, Seshadri G, Ramasamy S, Muthurajan R, Karuppasamy KS. 2023. Identification of newer stable genetic sources for high grain number per panicle and understanding the gene action for important panicle traits in rice. *Plants*, *12*(2), 1–18. https://doi.org/10.3390/plants12020250

Harsono A, Harnowo D, Ginting E, Elisabeth DAA. 2021. Soybean in Indonesia: current status, challenges and opportunities to achieve self-sufficiency. In J. C. Jimenez-Lopez & A. Clemente (Eds.), *Legumes Research - Volume 1*. IntechOpen. https://doi.org/10.5772/intechopen.101264

Hawalid H. 2019. Respon pertumbuhan dan produksi tanaman kacang tanah (*Arachis hypogaea* L.) pada pemberian takaran pupuk organik cair limbah tahu dan jarak tanam yang berbeda. *Klorofil*, *xiv*(2), 78–82.

Heryani N, Rejekiningrum P. 2020. Pengembangan pertanian lahan kering iklim kering melalui implementasi panca kelola lahan. *Jurnal Sumberdaya Lahan*, *13*(2), 63–71. https://doi.org/10.21082/jsdl.v13n2.2019.63-71

Hilty J, Muller B, Pantin F, Leuzinger S. 2021. Plant growth: the what, the how, and the why. *New Phytologist*, *232*(1), 25–41. https://doi.org/10.1111/nph.17610

Homulle Z, George, TS, Karley AJ. 2022. Root traits with team benefits : understanding belowground interactions in intercropping systems. *Plant and Soil*, *417*, 1–26. https://doi.org/10.1007/s11104-021-05165-8

Idaryani, Warda, Dahamarudin L. 2017. Karakter agronomis dan hasil beberapa varietas unggul padi pada lahan kering di Kabupaten Jeneponto. *Prosiding Seminar Nasional: Mewujudkan Kedaulatan Pangan Pada Lahan Sub Optimal Melalui Inovasi Teknologi Pertanian Spesifik Lokasi*, 202–207.

IP2TP. 2000. Budidaya Kacang Tanah di Lahan Kering. *Instalasi Penelitian dan Pengkajian Teknologi Pertanian Mataram, Lembar Informasi Pertanian (Liptan) IP2TP Mataram No. 09/Liptann/2000*, 2–4.

Iwuagwu C, Umechuruba C, Ononuju C, Nwogbaga A, Salaudeen M, Onejeme F. 2019. Effect of intercropping rice with maize and soybeans on disease incidence, severity and yield of rice in Abia State. *International Journal of Agricultural Science*. *4*, 23–28. http://iaras.org/iaras/journals/ijas

Jarrar H, El-Keblawy A, Ghenai C, Abhilash PC, Bundela AK, Abideen Z, Sheteiwy MS. 2023. Seed enhancement technologies for sustainable dryland restoration: Coating and scarification. *Science of The Total Environment*, *904*, 150–166. https://doi.org/https://doi.org/10.1016/j.scitotenv.2023.166150

Kalaitzidis A, Kadoglidou K, Mylonas I, Ghoghoberidze S, Ninou E, Katsantonis D. 2025. Investigating the impact of tillering on yield and yield-related traits in European rice cultivars. *Agriculture; Basel*, *15*(6).

Karunarathna B, Maduwanthi AKMRB. 2022. Competition indices used to evaluate the agronomic and monetary advantage in intercropping: A review. *AGRIEAST: Journal of Agricultural Sciences*, *16*(1), 25–40. https://orcid.org/0000-0002-3773-9402 25

Kebede E. 2021. Contribution, utilization, and improvement of legumes-driven biological nitrogen fixation in agricultural systems. *Frontiers in Sustainable Food Systems*, *5*, 1–18. https://doi.org/10.3389/fsufs.2021.767998

Khanal U, Stott KJ, Armstrong R, Nuttall JG, Henry F, Christy BP, Mitchell M, Riffkin PA, Wallace AJ, Mccaskill M, Thayalakumaran T, Leary GJO. 2021. Intercropping — evaluating the advantages to broadacre systems. *Agriculture*, *11*(453), 1–20. https://doi.org/https://doi.org/10.3390/agriculture11050453

Khasanah N, van Noordwijk M, Slingerland M, Sofiyudin M, Stomph D, Migeon AF, Hairiah K. 2020. Oil palm agroforestry can achieve economic and environmental gains as indicated by multifunctional land equivalent ratios. *Frontiers in Sustainable Food Systems*, *3*(January), 1–13. https://doi.org/10.3389/fsufs.2019.00122

Khatun M, Sarkar S, Era FM, Islam AKMM, Anwar MP, Fahad S, Datta R, Islam AKMA. 2021. Drought stress in grain legumes: effects, tolerance mechanisms and management. *Agronomy*, *11*(12). https://doi.org/10.3390/agronomy11122374

Kokkini M, Gazoulis I, Danaskos M, Kontogeorgou V, Kanatas P, Travlos I. 2025. Enhancing ecosystem services in agriculture: the special role of legume intercropping. *Frontiers in Sustainable Food Systems*, *9*, 1547879.

Kumar A, Taparia M, Madapu A, Rajalakshmi P, Marathi B, Desai UB. 2020. Discrimination of filled and unfilled grains of rice panicles using thermal and RGB images. *Journal of Cereal Science*, *95*, 1–9. https://doi.org/10.1016/j.jcs.2020.103037

Liu H, Gao X, Li C, Cai Y, Song X, Zhao X. 2025. Intercropping increases plant water availability and water use efficiency: A synthesis. *Agriculture, Ecosystems & Environment*, *379*, 109360. https://doi.org/https://doi.org/10.1016/j.agee.2024.109360

Lu S, Song Z, Chen W, Qian T, Zhang Y, Chen M, Li G. 2021. Counting dense leaves under natural environments via an improved deep-learning-based object detection algorithm. *Agriculture (Switzerland)*, *11*(10), 1–16. https://doi.org/10.3390/agriculture11101003

Luo D, Lin H. 2025. Evaluation of drought-tolerant legume varieties under rainfed conditions. *Field Crop*, *8*(3), 126–138. https://doi.org/10.5376/fc.2025.08.0013

Mead R, Willey RW. 1980. The Concept of a 'Land Equivalent Ratio' and Advantages in Yields from Intercropping. Experimental Agriculture, 16(3), 217–228.

Meirelles FC, Cavalcante AG, Gonzaga AR, Coelho AP, van der Werf W, Bastiaans L, Arf O, Lemos LB. 2024. Relative sowing time and spatial arrangement in upland rice/legume intercropping systems. *International Journal of Plant Production*, *18*(2), 161–174. https://doi.org/10.1007/s42106-024-00294-3

Mishra P, Singh U, Pandey CM, Mishra P, Pandey G. 2019. Application of student's t-test, analysis of variance, and covariance. *Annals of Cardiac Anaesthesia*, *22*(4), 407–411. https://doi.org/10.4103/aca.aca_94_19

Nandhini DU, Somasundaram E. 2020. Intercropping – A substantial component in sustainable organic agriculture. *Ind. J. Pure App. Biosci*. *8*(2), 133–143.

Neamatollahi E, Jahansuz MR, Mazaheri D, Bannayan M. 2013. Intercropping. In E. Lichtfouse (Ed.), *Sustainable Agriculture Reviews, vol 12.* (pp. 119–142). Springer Netherlands. https://doi.org/10.1007/978-94-007-5961-9_4

Oldeman RL. 1980. The agroclimatic classification of rice-growing environments in Indonesia. In *World Meteorological Organization; International Rice Research Institute: Proceedings of a symposium on the agrometeorology of the rice crop* (pp. 47–55).

Ozioma EM, Nwabunwanne OE, Ukaoba ME, Daniel OI. 2024. Substitutive effects of upland rice and soybean plant populations on the performance of the component crops in intercropping system. *System*, *12*(8), 13.

Paiman, Ardiyanta, Kusumastuti CT, Masulili A, Yussof SF. 2023. A review on the advantages of Jajar Legowo planting system in rice (*Oryza sativa* L .) cultivation. *Res. Crop*, *24*(3), 433–441. https://doi.org/10.31830/2348-7542.2023.ROC-966

Papong JR, Cagasan UA. 2020. Growth and yield performance of upland rice (*Oryza sativa* L . var . zambales) intercropped with mungbean *(Vigna radiata L .)* and peanut *(Arachis hypogaea L .).*International Journal of Agriculture, Forestry and Life Sciences *1*, 34–41.

Parida AK, Sekhar S, Panda BB, Sahu G. 2022. Effect of Panicle Morphology on Grain Filling and Rice Yield : Genetic Control and Molecular Regulation. *Frontiers in Genetics*, *13*, 1–23. https://doi.org/10.3389/fgene.2022.876198

Peraturan Daerah Kabupaten Banyumas Nomor 12 Tahun 2024. 2024. *Rencana perlindungan dan pengelolaan lingkungan hidup TAHUN 2024-2054.* https://static.banyumaskab.go.id/jdih/file/Peraturan-Nomor-12-Tahun-2024-tentang-peraturan-daerah-kabupaten-banyumas-nomor-12-tahun-2024-tentang-rencana-perlindungan-dan-pengelolaan-lingkungan-hidup-tahun-2024-2054.pdf

Pokharel SS, Yu H, Fang W, Parajulee MN, Chen F. 2023. Intercropping cover crops for a vital ecosystem service: a review of the biocontrol of insect pests in tea agroecosystems. *Plants*, *12*(12), 1–14. https://doi.org/10.3390/plants12122361

Rambe SSM, Calista I, Wulandari TN, Saragih A. 2024. Budidaya Tanaman Padi Gogo Terstandar. In *Balai Penerapan Standar Instrumen Pertanian (BPSIP) Bengkulu*.

Raza MA, Cui L, Qin R, Yang F, Yang W. 2020. Strip-width determines competitive strengths and grain yields of intercrop species in relay intercropping system. *Scientific Reports*, *10*(1), 1–12. https://doi.org/10.1038/s41598-020-78719-y

Raza MA, Din AMU, Zhiqi W, Gul H, Ur Rehman S, Bukhari B, Haider I, Rahman MHU, Liang X, Luo S, El Sabagh A, Qin R, Zhongming M. 2023. Spatial differences influence nitrogen uptake, grain yield, and land-use advantage of wheat/soybean relay intercropping systems. *Scientific Reports*, *13*(1), 1–15. https://doi.org/10.1038/s41598-023-43288-3

Ruillé M, Beillouin D. 2026. Ecological drivers of intercropping performance for enhanced global crop production. *Npj Sustainable Agroculture*, *4*(8), 1–9. https://doi.org/https://doi.org/10.1038/s44264-025-00110-z Ecological

Saraswati E, Gunawati ES, Pudyantini A. 2006. Identifikasi komoditas unggulan sektor pertanian tanaman pangan di wilayah Kabupaten Banyumas. *Eko-Regional*, *1*(2), 117–123.

Simanulang ZA. 2008. *75-Padi-Gogo-Varietas-Situ-Bagendit.*

Singh CM, Singh P, Tiwari C, Purwar S, Kumar M, Pratap A, Singh S, Chugh V, Mishra AK. 2021. Improving drought tolerance in mungbean (*Vigna radiata* L . Wilczek): Morpho-physiological, biochemical and molecular perspectives. *Agronomy*, *11*(1534), 1–20. https://doi.org/https://doi.org/10.3390/agronomy11081534

Sution, Nurdin M. 2015. Keragaan beberapa varietas unggul baru padi sawah irigasi semi teknis tanam pada musim kemarau. *Balai Pengkajian Teknologi Pertanian Kalimantan Barat*, *6*(45), 250–255.

Thilakarathna MS, McElroy MS, Chapagain T, Papadopoulos YA, Raizada MN. 2016. Belowground nitrogen transfer from legumes to non-legumes under managed herbaceous cropping systems. A review. *Agronomy for Sustainable Development*, *36*(4), 1–16. https://doi.org/10.1007/s13593-016-0396-4

Turnage G. 2022. Sampling submersed aquatic plant biomass: fresh vs. dry weight. In *Geosystems Research Institute, Mississippi State University.*

Wang W, Wang BZ, Zhang W, Li MY, Li JM, Ji SJ, Abrar M, Rehman MMU, Khan W, Tao HY, Sheteiwy MS, Wang WY, Xiong YC. 2026. Cereal-legume intercropping stabilizes yield and economic advantages under variable rainfall in semiarid rainfed environment. *European Journal of Agronomy*, *174*, 127942. https://doi.org/https://doi.org/10.1016/j.eja.2025.127942

Wang X, Wu Z, Zhou Q, Wang X, Song S, Dong S. 2022. Physiological response of soybean plants to water deficit. *Frontiers in Plant Science*, *12*(809692), 1–12. https://doi.org/10.3389/fpls.2021.809692

Wang X, Zou D, Li C, Zhou W, Li K, Tang Q, Zhu X, Li X, Cao L. 2024. Analysis of characteristics of rice tillering dynamics influenced by sowing dates based on DTM. *Heliyon*, *10*(19).

Wang Y, Han X, Zhao X, Zhang Y. 2024. Grain yield and interspecific competition in an oat-common vetch intercropping system at varying sowing density. *Plant Science*, *15*, 1–13. https://doi.org/10.3389/fpls.2024.1344110

Wang Z, Li Y, Su X, Tao S, Feng X, Wang Q, Xu X, Liu Y, Michaletz ST, Shrestha N, Larjavaara M, Enquist BJ. 2019. Patterns and ecological determinants of woody plant height in eastern Eurasia and its relation to primary productivity. *Journal of Plant Ecology*, *12*(5), 791–803. https://doi.org/10.1093/jpe/rtz025

Wenham K, Williams A, Rossignol T, Collins M. 2019. *Critical period of moisture vulnerability in mungbeans*. GRDC. https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2020/08/critical-period-of-moisture-vulnerability-in-mungbeans

Willey RW, Rao MR. 1980. A competitive ratio for quantifying competition between intercropS. *Expl Agric*, *16*(104), 117–125. https://doi.org/https://doi.org/10.1017/S0014479700010802

Winazira A, Ilyas I, Sufardi S. 2021. Status dan kendala kesuburan tanah pada lahan tegalan dan kebun campuran di Kecamatan Blang Bintang Kabupaten Aceh Besar. *Jurnal Ilmiah Mahasiswa Pertanian*, *6*(2), 79–87. https://doi.org/10.17969/jimfp.v6i2.16950

Wu L, Weston LA, Zhu S, Zhou X. 2023. Rhizosphere interactions: root exudates and the rhizosphere microbiome. In *Frontiers in plant science*, 14, 1–4. https://doi.org/10.3389/fpls.2023.1281010

Xi Y, Du YL, Wang D, Ren JY, Luo WY, Peng Q, Fang WY, Li FM. 2024. Wheat genetic progress in biomass allocation and yield components: A global perspective. *Field Crops Research*, *318*, 109617. https://doi.org/https://doi.org/10.1016/j.fcr.2024.109617

Xu Y, Chu C, Yao S. 2021. The impact of high-temperature stress on rice: Challenges and solutions. *Crop Journal*, *9*(5), 963–976. https://doi.org/10.1016/j.cj.2021.02.011

Yue B, Jin Y, Wu S, Tan J, Chen Y, Zhong H, Chen G, Deng Y. 2025. Research on SPAD inversion of rice leaves at a field scale based on machine vision and leaf segmentation techniques. *Agriculture (Switzerland)*, *15*(12), 1–24. https://doi.org/10.3390/agriculture15121270

Yue X, Hu Y, Zhang H, Schmidhalter U. 2020. Evaluation of both spad reading and spad index on estimating the plant nitrogen status of winter wheat. *International Journal of Plant Production*, *14*(1), 67–75. https://doi.org/10.1007/s42106-019-00068-2

Zhang Y, Liang K, Zhu F, Zhong X, Lu Z, Chen Y, Pan J, Lu C, Huang J, Ye Q, Yin Y, Peng Y, Mo Z, Fu Y. 2024. Differential study on estimation models for indica rice leaf spad value and nitrogen concentration based on hyperspectral monitoring. *Remote Sensing*, *16*(23), 1–16. https://doi.org/10.3390/rs16234604

Zhen X, Huo W, Sanz-Saez A, Miao Y, Chen CY, Batchelor WD. 2024. Drought-tolerant peanut (*Arachis hypogaea* L.) varieties can mitigate negative impacts of climate change on yield in the Southeastern U.S. *Computers and Electronics in Agriculture*, *224*(109105). https://doi.org/https://doi.org/10.1016/j.compag.2024.109105

Zustovi R, Landschoot S, Dewitte K, Verlinden G, Dubey R, Maenhout S, Haesaert G. 2024. Intercropping indices evaluation on grain legume-small grain cereals mixture : a critical meta-analysis review. *Agronomy for Sustainable Development*, *44*(5), 1–21. https://doi.org/10.1007/s13593-023-00934-4