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Evaluation of Soybean (*Glycine max* (L.) Merr.) Varieties for Tolerance to Relay Intercropping with Chili (*Capsicum annuum* L.) in Coastal Sandy Land

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ABSTRACT

The relay intercropping of soybean (*Glycine max* (L.) Merr.) planted between rows of chili (*Capsicum annuum* L.) in coastal sandy soils presents a potential strategy for increasing soybean production in Indonesia. This study aimed to evaluate the performance of soybean varieties for tolerance to relay intercropping with chili in coastal sandy lands based on yield, yield index, and plant growth. The research was conducted at Samas Beach, Bantul Regency, Yogyakarta, from January to May 2023, using a randomized complete block design with two factors and three blocks. Five soybean varieties ('Anjasmoro', 'Dena 1', 'Demas 1', 'Grobogan', and 'Malika'), and two cropping systems (monoculture and relay intercropping) were evaluated. Water was irrigated when rainfall was insufficient to maintain adequate soil moisture levels. Data were analyzed using *t*-test, ANOVA, Principal Component Analysis, Cluster Analysis, and Pearson's correlation. The results showed that relay intercropping significantly enhanced the seed yield of all soybean varieties compared to the monoculture, with 'Anjasmoro' showing the highest increase of 443.39%. Differences among the varieties under the relay intercropping system showed that 'Anjasmoro', 'Malika', 'Demas 1', and 'Dena 1' consistently outperformed 'Grobogan' in terms of yield and growth. The varieties were grouped into high-yielding ('Anjasmoro', 'Malika', 'Demas 1', and 'Dena 1') and low-yielding ('Grobogan'). High-yielding varieties had high positive correlations with the yield index (*r*=0.98), harvest index (*r*=0.61), and 100-SW (*r*=0.64). These findings

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suggest that utilizing high-yielding soybean varieties in relay intercropping with chili could significantly enhance soybean yields in coastal sandy lands.

Keywords: Coastal sandy land, monocropping, relay intercropping, soybean, yield

INTRODUCTION

Soybean (*Glycine max* (L.) Merrill) is one of the world's most important food crops and is consumed as a source of vegetable protein and oil (Wu et al., 2017). In Indonesia, soybeans are highly valued as the main side dish. According to the Agricultural Data and Information Center (2021), approximately 90% of soybeans are used for the industrial production of tempeh (50%) and tofu (39%), and 11% of soybeans are used as raw materials in the food industry. Therefore, soybean cultivation must be developed through the extensification of suboptimal land, such as coastal sandy land. Planting soybeans on fertile land is challenging because they are less competitive than other strategic crops, such as rice and corn.

Yogyakarta, a province in Indonesia, offers a potential solution to its coastal sandy land, accounting for approximately 3.300 ha or 4% of the total area, extending along 110 km of the southern coast of Indonesia (Yuwono, 2009). This land has considerable potential for soybean crop development because of its abundant, relatively shallow groundwater and high sunlight. However, coastal sandy lands are marginal and have low productivity. The low productivity of coastal sandy lands is caused by several limiting factors, such as low water-holding capacity, high infiltration, low amounts of organic matter, and low water-use efficiency (Lipiec & Usowicz, 2021; Wu et al., 2019). Technological innovations can improve productivity in coastal sandy lands, including soil conditioners and fertilizers, irrigation, waterproofing, mulching, windbreaks, and biofertilizer inoculation (Indradewa, 2021).

Farmers in Yogyakarta's coastal sandy area grow chili as a valuable commodity crop because of its economic value (Istiyanti et al., 2015; Nugroho et al., 2018). Chili has adapted well to these regions as an essential commodity and provides high profitability. Therefore, relay intercropping offers a promising approach to increasing land use efficiency by introducing soybean as a second crop alongside chili, which allows for more effective use of resources such as water, sunlight, and nutrients. Relay intercropping of soybeans has been widely practiced in various regions around the world, including Asia (Hussain et al., 2020; Suntari et al., 2023; Zhou et al., 2019), Africa (Kermah et al., 2019; Namatsheve et al., 2020), America (Cecchin et al., 2021; Shrestha et al., 2021), and Europe (Koskey et al., 2022; Leoni et al., 2022).

Relay intercropping involves planting two or more crops in the same field at different times during different parts of the life cycle of each crop. This method ensures that the second crop is introduced after the first crop has reached its reproductive growth stage but before it is ready for harvest (Andrews & Kassam, 1976). This staggered planting strategy minimizes competition for essential resources. It helps optimize crop growth and productivity, making it particularly valuable in resource-limited soils, such as those in coastal sandy areas. Relay intercropping has the advantages of enhanced resource-use efficiency (Ahmed et al., 2020; Chen et al., 2017; Rahman et al., 2017) and reduced pest and disease infestations (Biszczak et al., 2020; Chang et al., 2020), making it a viable option for improving agricultural productivity in coastal sandy lands.

The selection of soybean cultivars plays an important role in determining the success of soybean cultivation via relay intercropping in coastal sandy lands. Several studies have been conducted to select soybean varieties tolerant to intercropping under various conditions. Permanasari et al. (2023) and Harsono et al. (2020) examined several soybean varieties' growth response and yield under dry conditions. Sundari et al. (2020) evaluated the tolerance of various soybean varieties to shading in intercropping with cassava. However, little information is available on soybean varieties effectively intercropped with chili in coastal sandy soils, highlighting a gap in the current research. By exploring the adaptability and yield potential of various soybean varieties, this study addresses this critical gap and seeks to enhance productivity through optimized soybean-chili intercropping practices.

Several soybean cultivars have been released and tested in Indonesia for adaptation to coastal sandy lands. These varieties include 'Anjasmoro', 'Dena 1', and 'Grobogan', with 2.23, 2.24, and 2.27 tons per hectare, respectively (Handriawan et al., 2017), 'Demas 1' with a seed yield of 59.03 g per plant (Faozi et al., 2018), and 'Malika' with a seed yield of 1.18 tons per hectare (Purnamasari et al., 2016). Therefore, this study evaluates and identifies high-yielding soybean varieties compatible with relay intercropping with chili in coastal sandy lands, specifically focusing on their adaptability and performance in terms of yield and growth parameters. This study aims to provide practical insights into sustainable agricultural practices in marginal coastal regions, providing farmers with evidence-based recommendations for soybean-chili intercropping.

MATERIALS AND METHODS

Materials and Experimental Site

The five varieties adapted to sandy soil were 'Anjasmoro', 'Dena 1', 'Demas 1', Grobogan', and 'Malika'. This study was conducted on Samas beach sand farmland, Bantul Regency, Yogyakarta (8°00′06.7 ″S, 110°15'32.7’ E), at an altitude of 10 m above sea level and a distance of ±100 m from the shoreline. This study was conducted during the rainy season from January to May 2023. The total rainfall during the study was 1244.12 mm, according to the National Aeronautics and Space Administration (NASA) (2024). The soil at the research site had a sandy texture (80%) with a pH (H_2O) of 7.63, organic C content of 0.12%, total N content of 0.35%, available P content of 129.90 ppm, available K content of 7.52 ppm, and cation exchange capacity (CEC) of 5.53 cmol (+) kg^{-1} (Table 1).

Table 1
Characteristics of the soil in the study area

No.	Soil characteristics	Value	Criteria*	Methods
1	Texture		loamy sand class	Oxidation H_2O_2+HCl, Gravimetry
	Clay (%)	1		
	Sand (%)	80		
	Dust (%)	19		
2.	pH (H_2O)	7.63	Slightly alkaline	H_2O Extract 1:5, pH Meter
3.	CEC cmol ((+) kg^{-1})	5.53	Low	Percolation of Ammonium Acetate, Titrimetry
4.	Organic C(%)	0.12	Very low	Walkey-Black, Spectrophotometry
5.	Total N %	0.35	Moderate	Kjeldahl
6.	Available P (ppm)	129.90	Very high	Olsen, Spectrophotometry
7.	Available K (ppm)	7.52	Very low	Morgan-Wolf, AAS

Note. Soil samples were analyzed at the Integrated Laboratory of the Indonesian Agricultural Environment Standardization Institute, Central Java, Indonesia. *Indonesian Soil Research Institute (2005)

Experimental Design

A soybean-chili relay intercropping system was used in the field experiments. The experiments were conducted using a two-factor randomized complete block design with three blocks as replicates. The first factor was five varieties: 'Anjasmoro', 'Dena 1', 'Demas 1', 'Grobogan', and 'Malika'. The second factor was the cropping system: monoculture and relay intercropping. The experimental plots measured 2.5 m × 4 m, and each treatment plot contained two beds. Each bed measured 1 m × 4 m with a height of 20–25 cm. Soybeans were planted 30 days before the transplantation of chili seedlings (Figure 1a). In relay intercropping, soybeans were planted between two rows of chili plants (Figure 1b). The spacing between the chili plants was 50 cm × 40 cm. Soybeans were planted between rows of chili plants with a spacing of 40 cm between soybean plants and 25 cm between chili plants. Conversely, in the soybean monoculture, soybeans were planted with a 20 × 40 cm spacing. Each monoculture and relay intercropping plot contained 200 (two seeds × 100 planting holes) and 40 (two seeds × 20 planting holes) plants, respectively.

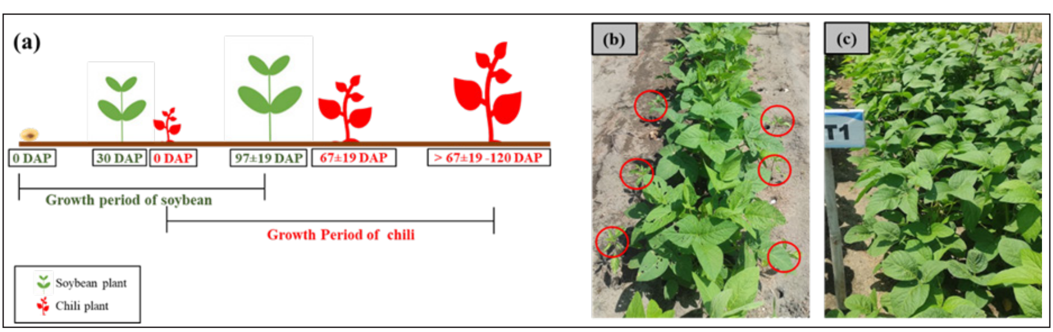

Figure 1. Illustration of the growth period of soybean-chili in relay intercropping systems (a), soybean-chili relay intercropping (b), and monoculture soybean (c)
Note. The circle in red indicates the chili plant

Experimental Procedure

The soil was plowed and fertilized with cow manure (20 $t.ha^{-1}$). Before planting, soybean seeds were mixed with Leguminosae inoculum (Legin®) at a rate of 30 g per 10 kg of seeds. Four soybean seeds were sown per planting hole, and thinning was conducted two weeks after germination to ensure only two plants per hole. Thinning was performed by cutting the stems at the base of the plants to avoid disturbing the root systems of the remaining plants. Soybeans were fertilized with urea (50 $kg.ha^{-1}$), SP36 (100 $kg.ha^{-1}$), and KCl (100 $kg.ha^{-1}$) at two weeks after planting (WAP) and NPK 15:15:15 (50 $kg.ha^{-1}$) at four WAP. Chili plants were fertilized at 1 WAP with NPK 15:15:15 (200 $kg.ha^{-1}$) and ZA (200 $kg.ha^{-1}$). The second supplementary fertilizer was given every week starting at 2–4 WAP in NPK 15:15:15 (125 $kg.ha^{-1}$) and ZA (125 $kg.ha^{-1}$). The third supplementary fertilizer was given every week starting at 5–8 WAP in the form of NPK 15:15:15 (150 $kg.ha^{-1}$) and ZA (150 kg. ha^{-1}). Applying fertilizer by pouring involves dissolving the fertilizer in water and then watering the plants with this solution during regular watering times. Watering was performed daily with a *pantek* well irrigation system, which pumps water from the ground and then flows it to the land using a pipe. Watering was applied using a pantek well irrigation system that pumped water from the ground and channeled it to the field through pipes. During rainy days or when soil moisture was adequate, irrigation was not performed to avoid overwatering. However, without rainfall, daily irrigation ensured the crops were not under water stress. Harvesting was performed after the plants had reached physiological maturity. The leaves turned brown and fell off, the pods and stems turned brown, and the seeds rattled when fully mature.

Growth, Yield Components, and Yield

Plant growth was determined by assessing plant height (cm), stem diameter (mm), number of branches, and leaf area (dm^2) at 8 weeks after planting (WAP), whereas plant dry biomass (g) was measured at harvest. Leaf area was measured using a leaf area meter (MK2, Delta-T Device Ltd., Serial No. CB380495, 220 V, 50 Hz, UK) using WinDIAS software (Delta-T Devices Ltd., UK). Yield components and yield variables were obtained at harvesting, including the number of pods, number of seeds, 100-seed weight (g), seed weight per plant (g), seed weight per plot (kg) and harvest index.

Soybeans were harvested from a 4 m^2 harvest area (subplot) in each plot. From this area, six plants were randomly selected as representative samples for each treatment at harvest to determine seed yield and dry weights of shoots and roots. These samples were carefully uprooted to prevent root loss and maintain the belowground biomass's integrity. After uprooting, the samples were sun-dried until they reached approximately 12% moisture content. Once dry, the seeds were manually threshed from the pods to determine the seed yield per plant. After the seeds were removed, the remaining whole plant biomass was oven-dried at 90 °C until a constant weight was achieved, and then the dry weights of the roots and shoots were measured separately. Seed weight per plot was determined for all seeds harvested from the 4 m^2 harvest area.

Harvest Index

The Harvest index was calculated as the ratio of seed weight and total aboveground dry biomass of six plants (Wang et al., 2020)

Leaf Nutrient Uptake

The uptake of nitrogen by the leaves was assessed at 8 WAP. Leaf nitrogen content was measured following the Kjeldahl method (Bremmer, 1996), and leaf nitrogen uptake was calculated using the following formula: leaf nitrogen uptake = leaf dry weight ($g.plant^{-1}$) × leaf N content ($g.g^{-1}$) (Chen et al., 2017).

The Yield Index (YI)

The yield index (YI) was calculated using YI = YR/mean YR (Gavuzzi et al., 1997), where YR is the soybean intercropping relay system yield.

Soil Analysis and Microclimate Research Site

At the beginning of the study, the soil was analyzed for texture (%clay, %sand, and %dust), pH (H_2O), CEC, organic C, total N, and nutrient availability (P and K). Soil moisture content was measured three times during the study: at 4 WAP (soybean-only phase), 8 WAP (soybean and chili co-growth phase), and harvest. Microclimate observations were acquired daily in the form of temperature and humidity. Rainfall data were obtained from the National Aeronautics and Space Administration (NASA) (2024).

Statistical Analysis

All observational data on monoculture and relay intercropping were compared using the Student's t-test in Excel. Analysis of variance (ANOVA) was used to determine the significance of varieties in the intercropping system using the Microsoft Excel version 2021 VBA add-in computer application (DSAASTAT ver 1.514) (Onofri & Pannacci, 2014). Duncan's mean separation test was also used. Principal component analysis (PCA) was performed to identify and highlight the key variables that significantly influenced the growth and yield characteristics of tolerant soybean varieties using Originpro 2024b. The grouping of varieties was based on the similarity of characters using a cluster analysis in Minitab. Pearson's correlation was used to determine the correlation between seed weight per plant and other variables using OriginPro 2024b. All data analyses were statistically significant at $p < 0.05$ and marginally significant at $p < 0.10$.

RESULTS AND DISCUSSION

Research Field Condition

The research site was on a coastal sandy land (Figure 2). The figure shows a landscape characterized by flat topography and sand-dominated soil, serving as the primary growing medium.

Figure 2. Coastal sandy land

The soil type at the research site was a sandy loam class, with 80% of the texture being sand. The soil sample was characterized by a slightly alkaline pH (H_2O) of 7.63; very low content of organic carbon (C), equal to 0.12%; moderate content of total nitrogen (N), equal to 0.35%; very high content of available phosphorus (P), equal to 129.90 ppm; very low content of available potassium (K), equal to 7.52 ppm; and low value of cation exchange capacity (CEC), equal to 5.53 cmol [+] kg^{-1} (Table 1). These properties limit sustainable soybean growth in the study area. The very low organic carbon content limits microbial activity and nutrient availability; the low CEC indicates a limited ability of soils to hold and supply essential nutrients, and the sandy texture is likely to result in rapid nutrient leaching. Very high phosphorus content limits plant nutrient availability at a slightly alkaline pH, causing the precipitation of calcium into insoluble compounds (Baccari & Krouma, 2023). Additionally, very low K content restricts plant growth because of its high mobility and leaching in sandy soils (Degryse & McLaughlin, 2014). Therefore, it is crucial to incorporate organic nutrients to mitigate these issues. Weil and Brady (2017) indicated that incorporating sufficient organic material, such as manure, may produce a healthy soil quality, which increases nutrient holding and availability. Approximately 15–20 tons per hectare should be applied to sandy soil to make it fertile (Indradewa, 2021).

Figures 3a and 3 b show the climatic conditions during the study period. As shown in Figure 3a, the monthly rainfall from January to mid–May ranged from 101.07 mm to 388.26 mm, with a relatively even distribution throughout the rainy season. Sumarno and Manshuri (2013) noted that soybeans require monthly rainfall between 120 mm and 135 mm for optimal growth. Despite the ample rainfall during the study period, good drainage of coastal sandy land prevented flooding and minimized the risk of plant root rot. As shown in Figure 3b, average temperature and relative humidity were recorded during the study period. The daytime temperatures are high on sandy land near the coast, having an average temperature variation ranging from 35.05 °C to 38.83 °C, while the air humidity fluctuates between 54.20% and 62.45%. These conditions are typical for coastal areas that receive intense solar radiation.

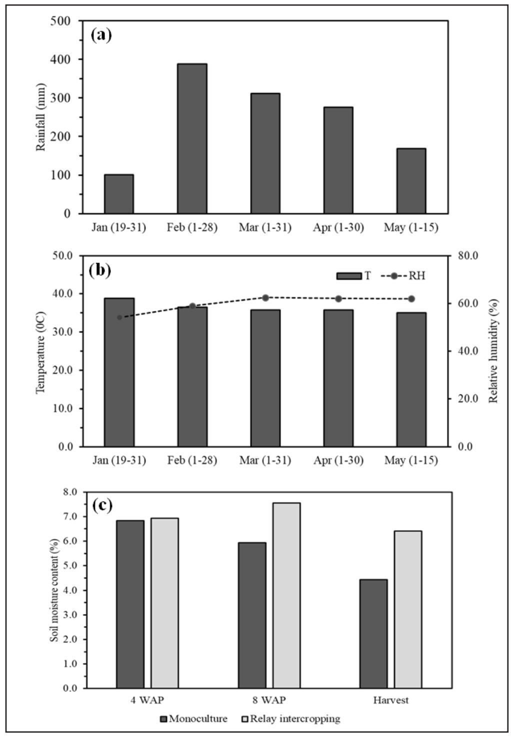

Figure 3. Monthly rainfall totals (a), average temperatures and relative humidity (b), and soil moisture content during the study (c)

Soil moisture levels varied between monoculture and relay intercropping systems (Figure 3c). At 4 WAP, soil moisture levels were similar between the two systems, with 6.83% in monoculture and 6.94% in relay intercropping. However, at 8 WAP and harvest, relay intercropping maintained higher soil moisture levels (7.56% and 6.42%, respectively) compared to monoculture (5.93% and 4.43%, respectively). This variation can likely be attributed to reduced intraspecific competition in the relay intercropping system, which enabled more efficient water usage and resource sharing between the soybean and chili crops. Additionally, water was irrigated when there was no rainy day or insufficient soil moisture, preventing drought stress and supporting the growth of soybeans and chilies in sandy soils with low water retention.

Yield and Yield Components

The weights of the soybean seeds in the monoculture and relay intercropping with chili are shown in Figure 4.

The cropping system significantly affected the weight of soybean seeds per plant (Figure 4a). The *t*-test results showed significant differences ($p < 0.05$) between monoculture

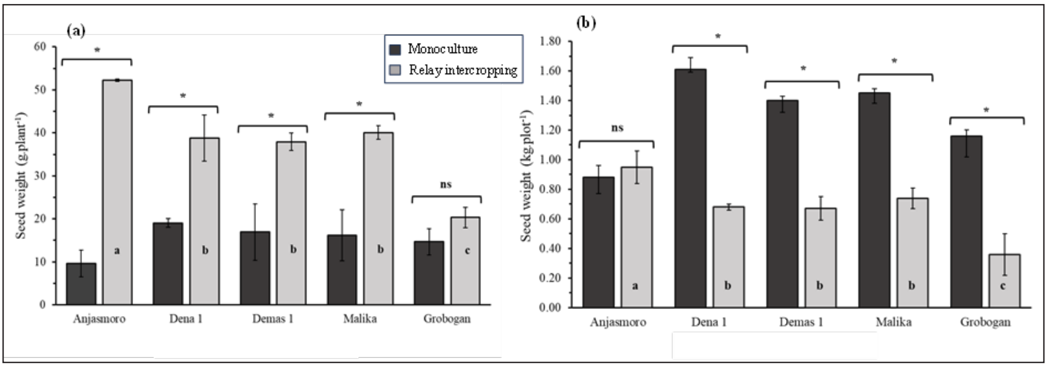

Figure 4. Seed weights per plant (g) (a) and plot (b) of five soybean varieties in monoculture and relay intercropping systems

Note. For each soybean variety in each cropping system, */ns denotes a significant/non-significant difference between monoculture and relay intercropping using a *t*-test at $p < 0.05$. Different letters within varieties in relay intercropping indicate significant differences using Duncan's Multiple Range test at $p < 0.05$. Means are averages over three replicates ± standard deviation

and relay intercropping for all varieties except 'Grobogan', which showed no significant difference. Relay intercropping increases seed production per plant, with all varieties, except 'Grobogan', producing significantly higher seed weights under relay intercropping than in monoculture. 'Anjasmoro' exhibited the greatest increase (443.39.87%), followed by 'Malika' (147.36%), 'Demas 1' (124.22%), 'Dena 1' (103.89%), and 'Grobogan' (38.71%). In relay intercropping, ANOVA revealed significant differences ($p < 0.05$) among varieties, with 'Anjasmoro' producing the highest seed weight per plant (52.21 g), followed by 'Malika' (40.08 g), 'Dena 1' (38.77 g), and 'Demas 1' (37.93 g), while 'Grobogan' produced the lowest (20.34 g).

For seed weight per plot (Figure 4b), the *t*-test results indicated significant differences ($p < 0.05$) between monoculture and relay intercropping for all varieties except 'Anjasmoro', which showed no significant difference. Relay intercropping resulted in significantly lower seed weights than monoculture due to the reduced soybean population, with only one row of soybeans planted between chili rows. This reduced population lowered total plot yields but minimized intraspecific competition, improving resource use efficiency per plant. However, 'Anjasmoro' showed no significant difference in seed weight per plot between the two systems, reflecting its superior adaptability to relay intercropping. ANOVA in relay intercropping revealed significant differences ($p < 0.05$) among varieties. 'Anjasmoro' had the highest seed weight (0.95 $kg.plot^{-1}$), followed by 'Malika' (0.74 $kg.plot^{-1}$), 'Dena 1' (0.68 $kg.plot^{-1}$), 'Demas 1' (0.67 $kg.plot^{-1}$), and 'Grobogan' (0.36 $kg.plot^{-1}$). The significant reduction in seed weight per plot under relay intercropping compared to monoculture underscores the trade-off between population density and individual plant performance. The yield and plant growth components further demonstrate the efficiency of soybean relay intercropping, as shown in Figures 5, 6, and Table 2.

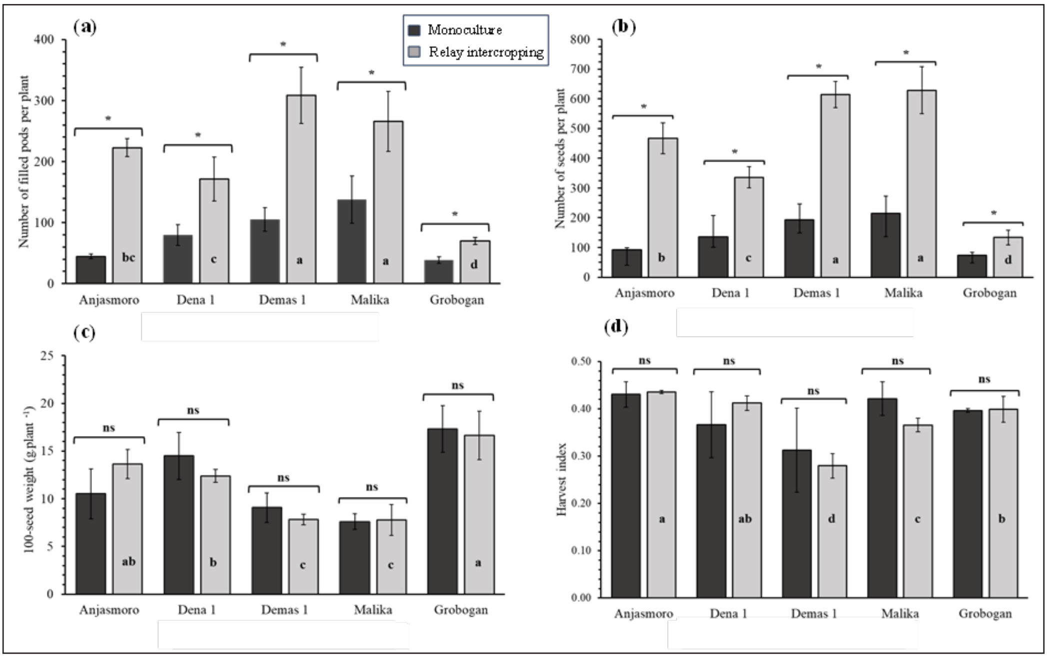

Figure 5. Number of filled pod plants (a), number of seeds per plant (b), 100-seed weight (c), and harvest index (d) of the five soybean varieties in the monoculture and relay intercropping systems
Note. For each soybean variety in each cropping system, */ns denotes a significant/non-significant difference between monoculture and relay intercropping using *a t*-test at $p < 0.05$. Different letters within varieties in relay intercropping indicate significant differences using Duncan's Multiple Range test at $p < 0.05$. Means are averages over three replicates ± standard deviation

The number of filled pods differed significantly ($p < 0.05$) between monoculture and relay intercropping for all varieties (Figure 5a). Relay intercropping produced more filled pods than monoculture. Among the varieties in the relay intercropping system, significant differences ($p < 0.05$) were observed, with 'Demas 1' and 'Malika' producing the highest number of filled pods, while 'Grobogan' produced the fewest.

Significant differences ($p < 0.05$) were found in the number of seeds per plant between monoculture and relay intercropping across all varieties (Figure 5b). Relay intercropping significantly increased the number of seeds per plant, with the greatest increase observed in 'Anjasmoro' (407%), followed by 'Demas 1' (217.80%), 'Malika' (193.54%), 'Dena 1' (146.91%), and 'Grobogan' (80.63%). Within the relay intercropping system, significant differences $p < 0.05$) were noted among the varieties, where 'Demas 1' and 'Malika' produced the highest number of seeds per plant, while 'Grobogan' had the fewest.

The 100-seed weight did not differ significantly ($p > 0.05$) between monoculture and relay intercropping (Figure 5c). However, significant differences ($p < 0.05$) were observed among the varieties in the relay intercropping system. Based on the standard classification of soybean seed size (Krisnawati & Adie, 2015), soybean seeds are categorized into three groups: small (<10 g/100 seeds), medium (10-14 g/100 seeds), and large (>14 g/100 seeds). In the relay intercropping system, 'Grobogan' had the largest seed size, averaging a weight of 16.26 g/100 seeds, classifying it as large. 'Anjasmoro' and 'Dena 1' were classified as medium-sized, with seed weights of 13.64 g and 12.39 g/100 seeds, respectively. In contrast, 'Demas 1' and 'Malika' were categorized as small-seeded varieties, weighing 7.82 g and 7.77 g/100 seeds, respectively. Although the maximum seed size is primarily determined by genetic traits, environmental conditions during the seed-filling stage also play a critical role in influencing final seed size (Suwitono et al., 2021)

The cropping system did not significantly affect the harvest index ($p > 0.05$) for any of the varieties, indicating that the efficiency of biomass partitioning between seed yield and vegetative growth was consistent across monoculture and relay intercropping systems (Figure 5d). However, significant differences ($p < 0.05$) were observed among the varieties in the relay intercropping system. 'Anjasmoro' recorded the highest harvest index (0.44), followed by 'Dena 1' (0.41), 'Grobogan' (0.40), 'Malika' (0.37), and 'Demas 1' with the lowest (0.28). A higher harvest index generally reflects a plant's ability to allocate more resources to seed production, which is crucial for maximizing the economic yield (Liu et al., 2020). Variations in the harvest index among varieties may be attributed to inherent genetic traits that influence biomass allocation efficiency (Wang et al., 2020).

Crop Growth Parameters

These measurements supported the quantitative determination of changes in crop growth parameters between the monoculture and relay intercropping systems. Plant height, stem diameter, and number of branches are crop growth parameters that determine soybean yield (Fattah et al., 2024; Xu et al., 2021; Zhang et al., 2021). Soybeans grown in relay intercropping had lower plant height, thicker stem diameter, and more branches than monoculture ones (Table 2).

The *t*-test results indicated that plant height differed significantly ($p < 0.05$) between monoculture and relay intercropping for 'Dena 1' and 'Demas 1', where monoculture consistently resulted in taller plants. However, for 'Anjasmoro', 'Malika' and 'Grobogan,' no significant differences ($p > 0.05$) were observed between the cropping systems. On average, plant height in monoculture (62.83 cm) was 17.69% higher than in relay intercropping (51.72 cm) (Table 2). The taller plants in monocultures are attributed to intraspecific competition, which induces stem elongation due to reduced light availability, as Klimek-Kopyra et al. (2020) reported. In the relay intercropping, ANOVA revealed significant differences ($p < 0.05$) among varieties. 'Malika' (59.28 cm), 'Anjasmoro' (56.00 cm), and 'Demas 1' (55.75 cm) had taller plant heights compared to 'Dena 1' (44.49 cm) and 'Grobogan' (43.08 cm), reflecting varietal differences in adaptation to the intercropping system.

Table 2
Plant height, stem diameter, and number of branches per plant at 8 WAP for five soybean varieties in monoculture and relay intercropping systems

Varieties	Plant height (cm)			Stem diameter (mm)			Number of branches		
	MC	**RC**	**D (%)**	**MC**	**RC**	**D (%)**	**MC**	**RC**	**D (%)**
'Anjasmoro'	61.21^{a}	56.00^{a} A	−8.51	0.58^{a}	0.97^{b} AB	66.67	3.33^{b}	7.39^{a} B	121.67
'Dena 1'	59.60^{a}	44.49^{b} B	−25.35	0.54^{a}	0.84^{b} AB	53.52	6.08^{a}	7.25^{a} B	19.18
'Demas 1'	75.33^{a}	55.75^{b} A	−26.00	0.76^{a}	1.13^{b} A	48.03	4.42^{b}	9.50^{a} A	115.09
'Malika'	64.19^{a}	59.28^{a} A	−7.66	0.67^{a}	0.95^{b} AB	40.15	5.50^{b}	7.62^{a} B	47.83
'Grobogan'	53.83^{a}	43.08^{a} B	−19.97	0.64^{a}	0.72^{a} B	11.55	3.83^{b}	5.67^{a} C	43.94
Average	62.83	51.72		0.64	0.92		4.63	7.54	

Note. Average values followed by the same lowercase letters in the horizontal direction and the same variable are not significantly different according to the *t*-test at $p < 0.05$, and those followed by uppercase letters in the vertical direction and the same variable are not significantly different according to Duncan's multiple range test at $p < 0.05$. M: Monoculture, RC: Relay intercropping, D: The difference between monoculture and relay intercropping

The *t*-test results indicated that stem diameter was significantly greater ($p < 0.05$) in relay intercropping compared to monoculture for all soybean varieties except 'Grobogan'. (Table 2). On average, stem diameter increased by 43.34% under relay intercropping. Among the varieties in relay intercropping, significant differences ($p < 0.05$) were observed. 'Demas 1' exhibited the largest stem diameter (1.13 mm), followed by 'Anjasmoro' (0.97 mm), 'Malika' (0.95 mm), and 'Dena 1' (0.84 mm), while 'Grobogan' had the smallest diameter (0.72 mm).

The number of branches per plant was significantly higher ($p < 0.05$) in relay intercropping, with an average increase of 62.83% compared to monoculture (Table 2). All varieties, except 'Grobogan', showed significant increases in branch number under relay intercropping. Significant differences ($p < 0.05$) were observed among varieties within the relay intercropping. 'Demas 1' produced the highest number of branches (9.50), followed by 'Malika' (7.62), 'Anjasmoro' (7.39), and 'Dena 1' (7.25), while 'Grobogan' had the fewest (5.67). These findings align with Rosso et al. (2021), who reported a positive correlation between soybean yield and the number of productive branches, underscoring their importance for pod development. Enhancing branch development in relay intercropping systems thus plays a critical role in improving soybean yields.

The improved growth and yield of soybeans in the relay intercropping system can be attributed to several synergistic factors that optimize resource utilization. Planting soybeans first allows early establishment, reducing direct competition for light, water, and nutrients during critical growth stages and promoting complementary rather than competitive resource use (Ahmed et al., 2020; Raza et al., 2023). Observed soil moisture data (Figure 3c) indicate that relay intercropping consistently maintains higher moisture levels than monoculture, particularly at 8 WAP and harvest, likely due to more efficient water use and reduced competition. Additionally, nutrient sharing within the relay intercropping system allows the fertilizers applied to chili to indirectly benefit soybeans, enhancing resource availability and yield (Chen et al., 2017; Wang et al., 2014). Relay intercropping strategically combines the timing of crop establishment and resource sharing, creating a synergistic effect that supports the observed higher yield of soybeans, highlighting its potential as a sustainable agricultural practice.

In relay intercropping, the leaf area across all tested varieties was significantly greater ($p < 0.05$) than that observed in the monoculture, exhibiting an average increase of 126.18%, as shown in Figure 6a. Among the varieties, 'Anjasmoro' showed the most pronounced increase in leaf area, reaching 216.15%. This enhanced growth in relay intercropping systems is attributed to the more efficient utilization of resources than monocultures. However, ANOVA within the relay intercropping system revealed no significant differences ($p > 0.05$) among the varieties, indicating that all varieties performed similarly in terms of leaf area under this system. Factors such as genotype and environmental conditions significantly influence leaf area, which in turn supports plant growth, biomass accumulation, and vigor owing to the role of photosynthesis in producing essential assimilates for plant survival (Du et al., 2022; Fattah et al., 2024).

All soybean varieties grown in relay intercropping showed significantly higher N uptake ($p < 0.05$) compared to those grown in monoculture, with N uptake ranging from 0.10 to 0.16 g of leaf dry weight^{-1} (Figure 6b). However, ANOVA revealed no significant differences ($p > 0.05$) in N uptake among the varieties within the relay intercropping system, indicating that nitrogen absorption efficiency was consistent across varieties in this planting system. The amount of N uptake aligns with shoot dry weight and seed yield. According to Permanasari et al. (2023), improved N content enhances leaf development because nitrogen participates in the formation and development of plant cell structures. The higher nutrient uptake in soybean relay intercropping was likely due to the additional fertilizer applied for chili plant growth during the same period. Compared with monocultures, crops grown in relay intercropping can use resources more efficiently to produce higher yields. Previous research has revealed that the superiority of relay intercropping over other systems results from using various complementary resources such as land and nutrients (Jensen et al., 2020; Raza et al., 2019).

Soybean varieties grown in monoculture and relay intercropping showed significant differences ($p < 0.05$) in root dry weight, except for the 'Demas 1' (Figure 6c). In relay intercropping, the root dry weight increased for 'Anjasmoro' by 148.78%, 'Dena 1'

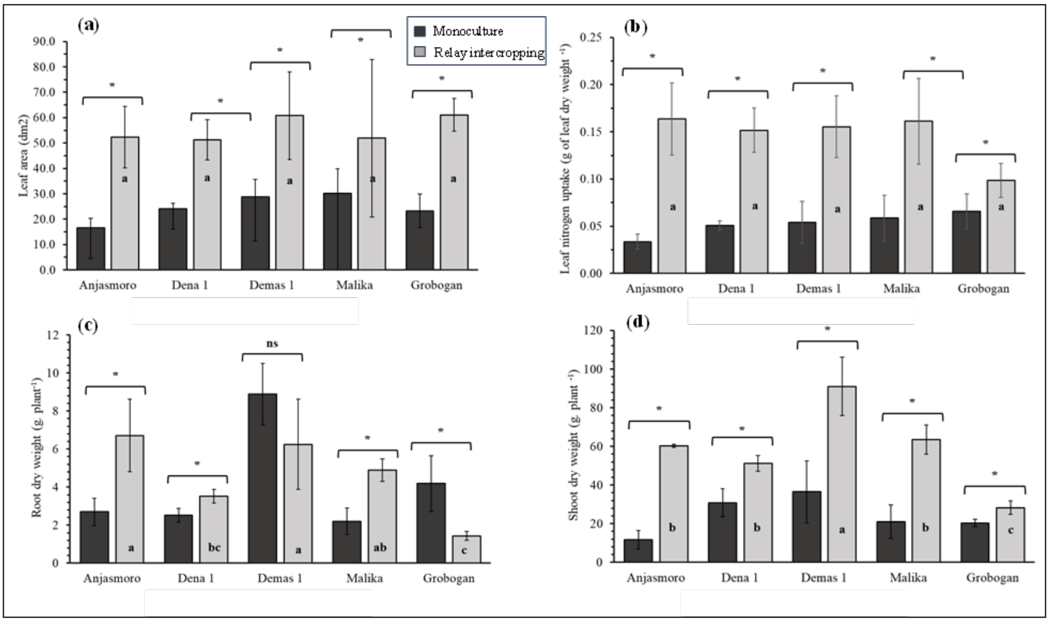

Figure 6. Leaf area (a) and leaf nitrogen uptake (b) at 8 WAP, and root dry weight (c) and shoot dry weight (d) at harvest of five soybean varieties in monoculture and relay intercropping
Note. For each soybean variety in each cropping system, */ns denotes a significant/non-significant difference between monoculture and relay intercropping using a *t*-test at $p < 0.05$. Different letters within varieties in relay intercropping indicate significant differences using Duncan's Multiple Range test at $p < 0.05$. Means are averages over three replicates ± standard deviation

by 39.80%, and 'Malika' by 121.79%. This indicates their adaptability to competitive intercropping conditions, likely enhancing their ability to absorb water and nutrients. Conversely, 'Demas 1' and 'Grobogan' exhibited decreased root dry weight by 29.70% and 65.66%, respectively, indicating a lower tolerance to interspecific competition for belowground resources. Despite this, 'Demas 1' maintained a relatively high root biomass (6.25 g), second only to 'Anjasmoro' (6.71 g), and achieved the highest shoot dry weight (91.03 g) (Figure 6d), reflecting a compensatory growth strategy that prioritizes aboveground productivity (Poorter et al., 2012; Sarto et al., 2021). This adaptive biomass allocation enables 'Demas 1' to sustain productivity under intercropping stress, unlike 'Grobogan,' which consistently exhibited lower biomass across all variables, highlighting its reduced competitiveness in such systems. (Lv et al., 2014; Sarto et al., 2021). Meanwhile, 'Malika,' 'Dena 1,' and 'Grobogan' recorded lower root dry weights at 4.89 g, 3.53 g, and 2.14 g, respectively, underscoring the variability in adaptability among the soybean varieties.

For shoot dry weight, all soybean varieties grown in monoculture and relay intercropping showed significant differences ($p < 0.05$) (Figure 6d). Relay intercropping significantly increased shoot dry weight, with the highest increase in the 'Anjasmoro' (416.65%), followed by 'Malika' (202.37%), 'Demas 1' (149%), 'Dena 1' (65%), and

'Grobogan' (39.21%). ANOVA within the relay intercropping system revealed significant differences ($p < 0.05$) among varieties. 'Demas 1' had the highest shoot dry weight (91.03 g), significantly exceeding the other varieties. 'Anjasmoro', 'Dena 1', and 'Malika' had similar shoot dry weights of 60.35 g, 51.14 g, and 63.58 g, respectively. The lowest shoot dry weight was found in the 'Grobogan' at 28.14 g. Shoot dry matter is related to the availability of resources such as adequate water and nutrients. Sufficient nutrients during soybean growth produce assimilates for pod formation. Raza et al. (2023) stated that the accumulation of dry matter increases the number and weight of soybean seeds, which are crucial for increasing soybean yields.

The Seed Weight, Yield Index, Principal Component Analysis, and Cluster Analysis of Five Soybean Varieties in Relay Intercropping

The average seed weight (YR) of the five varieties in the soybean relay intercropping was 37.86 g. 'Anjasmoro', 'Dena 1', 'Demas 1', and 'Malika' had above-average yields of 52.21 g, 38.71 g, 37.93 g, and 40.08 g, respectively (Figure 7a). In contrast, 'Grobogan' had a lower yield (20.34 g), compared to the other four varieties and below the average yield of 37.86 g. The YR values were consistent with the yield index (YI), where a high YI value indicated tolerance to relay intercropping. Figure 7b shows that 'Anjasmoro', 'Dena 1', 'Demas 1', and 'Malika' had a high YI value of ≥ 1, while 'Grobogan' had the lowest YI value of ≤ 1. The high YR and Y1 values of 'Anjasmoro', 'Dena 1', 'Malika 1', and 'Dena 1' indicate that the four varieties were high-yielding soybean varieties, whereas 'Grobogan' was a low-yielding variety.

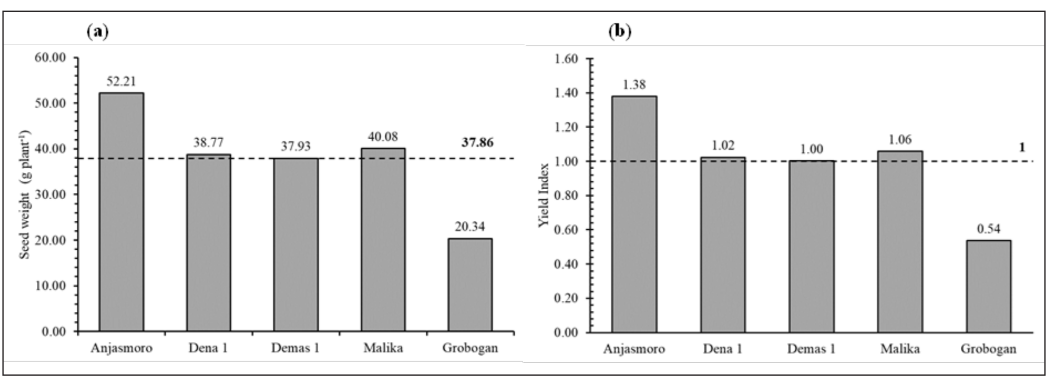

Figure 7. Average seed weight (a) and yield index (b) of five soybean varieties in relay intercropping

Principal Component Analysis (PCA) was conducted to identify and highlight the key variables that significantly influenced the growth and yield characteristics of tolerant soybean varieties. The two main components (PC1 and PC2) explained 88.87% of the total data variability (Figure 8a). PC1 explained 63.64%, and PC2 explained 25.23% of the variability, respectively. The number of pods, seeds, branches, and stem diameters significantly contributed to PC1, with values of 0.35, 0.34, 0.33, and 0.33, respectively. These variables indicate that PC1 was primarily associated with growth and yield components, emphasizing vegetative growth and reproductive output. The seed weight per plant, harvest index, shoot dry weight, root dry weight, and yield index contributed significantly to PC2, with values of 0.41, 0.39, -0.41, -0.41, and -0.41, respectively. The positive contributions of seed weight and yield index suggest that PC2 reflects the yield efficiency. In contrast, the negative contributions of root and shoot dry weights indicate an inverse relationship between vegetative biomass and yield efficiency.

'Anjasmoro' had a high PC2 value, indicating superiority in seed weight and yield index variables. 'Demas 1' had a high value on PC1, showing superiority in the number of pods and seeds and strong vegetative growth components like the number of branches and stem diameter. Conversely, 'Grobogan' had a high negative value for both components, indicating significant differences in the measured variables, and tended to have low yields. 'Dena 1' and 'Malika' had values closer to the average on both components, indicating more balanced growth and yield characteristics without extreme dominance in either direction.

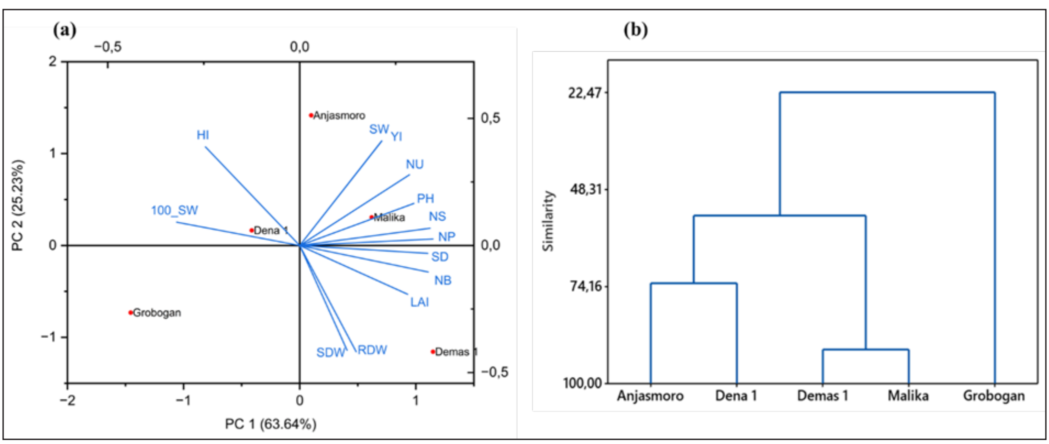

Figure 8. Principal component analysis (a) and cluster analysis (b) were based on the growth, yield components, yield, and yield index of soybean plants in relay intercropping

Note. PH: plant height, NB: number of branches, SD: stem diameter, SDW: shoot dry weight, RDW: root dry weight, LA: leaf area, NU: leaf nutrient uptake, NP: number of pods, NS: number of seeds, HI: harvest index, SW: seed weight, YI: yield index

Cluster analysis based on the PCA results showed that the two groups of tolerant soybean varieties had high and low yields (Figure 8b). 'Anjasmoro,' 'Dena 1,' 'Demas 1,' and 'Malika' are grouped as high-yielding varieties at a 55.35% similarity level. The PCA biplot supported this grouping, indicating that these varieties share similar characteristics, such as above-average seed weight and yield index (YI) ≥ 1, and strong similarities in plant growth variables, showing good tolerance in the intercropping system. In contrast, the 'Grobogan' is identified as low-yielding, with the lowest similarity level of 22.47% and significant differences from the other varieties. This finding is consistent with the PCA results, where 'Grobogan' is distinctly separated from other varieties in the biplot due to its low seed weight (20.34 g) and yield index of ≤ 1 (0.54). The integration of these analyses provides a comprehensive classification of soybean varieties based on their yield performance and growth characteristics.

Pearson's Correlation in High and Low-yielding Tolerant Soybean Varieties

The correlation between the high- and low-yielding soybean groups reveals key differences in how these varieties allocate resources and manage growth to influence yield outcomes. The correlation of the high- and low-yielding soybean groups is shown in Figure 9.

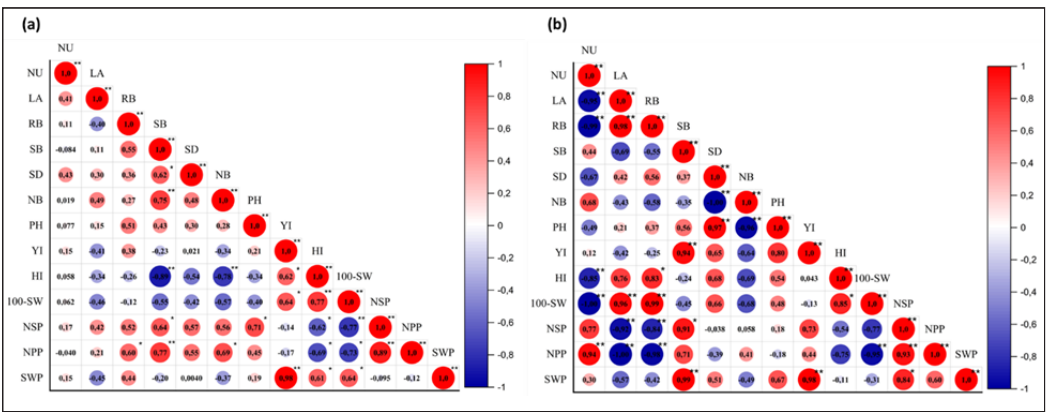

Figure 9. (a) Pearson correlation analysis of the high-yielding ('Anjasmoro', 'Dena1', 'Demas 1' and 'Malika') and (b) low-yielding ('Grobogan') tolerant soybean varieties

Note. PH: plant height, NB: number of branches, SD: stem diameter, SDW: shoot dry biomass, RDW: root dry biomass, LA: leaf area, NU: leaf nutrient uptake, NP: number of pods, NS: number of seeds, HI: harvest index, SWP: seed weight, YI: yield index. * and ** indicate statistically significant correlations at $p < 0.05$ and $p < 0.01$, respectively

Significant correlations were observed in high-yielding tolerant soybean varieties ('Anjasmoro', 'Dena 1', 'Demas 1', and 'Malika') (Figure 9a). In the high-yielding group, significant positive correlations were observed between seed weight per plant (SWP) and 100-seed weight (100-SW) ($r = 0.64$*), yield index (YI) ($r = 0.98$ **), and harvest index (HI) ($r = 0.61$*). These correlations suggest that these varieties efficiently convert growth resources into higher seed yields by balancing seed size and quantity without compromising overall productivity. Furthermore, the number of pods per plant (NPP) and number of seeds per plant (NSP) were strongly positively correlated with shoot dry weight (SDW) (NPP: $r = 0.77$**; NSP: $r = 0.64$*) and root dry weight (RDW) (NPP: $r = 0.60$*). This indicates that robust vegetative growth contributes significantly to the increase in pod and seed numbers, which supports the higher yields observed in these varieties.

In contrast, the low-yielding variety 'Grobogan' exhibits weaker and often non-significant correlations between SWP and similar variables. While a positive correlation exists between SWP and NPP (r = 0.61) and NSP (r = 0.84), these relationships were not statistically significant, indicating that they were not strong or consistent enough to support significant yield improvements. Moreover, the HI, which indicates the efficiency of converting biomass into seed yield, does not show a significant correlation in 'Grobogan'. This suggests inefficiencies in the utilization of biomass for seed production. The negative correlation between SWP and 100-SW (r = -0.32) in 'Grobogan' further indicates a trade-off where increasing seed size reduces the total seed weight per plant, exacerbating the inefficiency in resource allocation.

Overall, the primary differences between the high- and low-yielding tolerant soybean varieties are their efficiency in using resources to produce seeds, their ability to balance seed size with the number of seeds, and the consistency with which these factors contribute to overall yield. The high-yielding group was more effective at converting growth resources into seed production, maintaining a good balance between producing a large number of seeds and a large number of seeds, leading to greater productivity. In contrast, the low-yielding group struggles to manage these resources efficiently, often increasing seed size at the expense of total seed number, thereby limiting their overall yield potential.

CONCLUSION

Five soybean varieties ('Anjasmoro', 'Dena 1', 'Demas 1', 'Malika', and 'Grobogan') were adapted to coastal sandy lands. Relay intercropping between soybeans and chili on coastal sandy lands has significantly improved soybean yield and growth components compared to monoculture systems, demonstrating its effectiveness in optimizing land use and resource utilization. Water was irrigated when there was no rainy day or insufficient soil moisture, which was critical in maintaining adequate soil moisture levels, preventing drought stress, and supporting the growth of soybeans and chilies throughout their life cycle. The five soybean varieties were classified into high-yielding ('Anjasmoro', 'Dena 1', 'Demas 1', and 'Malika') and low-yielding ('Grobogan') groups based on yield, yield components, and plant growth. These findings suggest that selecting high-yielding soybean varieties can maximize productivity in relay intercropping systems.

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