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Agronomic performance of soybeans in double-row soybean-maize intercropping systems under drought conditions in dryland areas

Kisman*[1)], Farid Hemon[1)], Suprayanti M. Dewi[2)], Idham Halid[3)], Firman A. Rahman[4)]

[1)] University of Mataram, Postgraduate Program, Master Program Study of Dryland Agriculture, Jl. Pendidikan 37, Mataram, Indonesia

[2)] University of Mataram, Faculty of Agriculture, Department of Agronomy, Program Study of Agroecotechnology, Jl. Majapahit 62, Mataram, Indonesia

[3)] Agriculture Office of Central Lombok Regency, Jl. Ahmad Yani No. 1, 83511 Praya, West Nusa Tenggara, Indonesia

[4)] Universitas Islam Negeri Mataram, Faculty of Education and Teacher Training, Department of Biology Education, Jl. Gadjah Mada Jempong No. 100, Mataram, Indonesia

* Corresponding author

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Abstract: This study investigates the agronomic performance of high-protein soybean varieties under various double-row intercropping patterns in drought-affected dryland areas of Lombok, Indonesia. The research utilised an experimental approach using a split plot design. The main plot comprised four levels of double-row intercropping patterns (B): (B1) soybean sole cropping with a spacing of 40:20:15 cm, (B2) soybean-maize intercropping with a spacing of 70:20:15 cm, (B3) soybean-maize intercropping with a spacing of 60:20:15 cm, and (B4) soybean-maize intercropping with a spacing of 50:20:15 cm. The subplot included five high-protein soybean varieties (V): 'Kemuning-1' (V1), 'Mutiara-2' (V2), 'Mutiara-3' (V3), 'Sugentan-2' (V4), and 'Gamasugen-2' (V5). Each combination was replicated three times. The assessed agronomic traits included plant height, trifoliate leave number, node number, branch number, trifoliate leaf area, days to flowering, pod number, filled pod number, percent of unfilled pod, grain number, 100-grain mass, grain mass per plant, and grain yield per hectare. The results showed that the B×V interaction significantly influenced agronomic traits, including the number of nodes and branches, as well as yield and its components. The varieties 'Kemuning-1', 'Mutiara-3', and 'Gamasugen-2' produced better grain yields in sole cropping and double-row intercropping systems, but exhibited greater crop reductions under double-row intercropping, indicating lower adaptability to the system. In contrast, the consistent grain yield stability of 'Mutiara-2' and 'Sugentan-2' showed greater efficiency under double-row intercropping systems, indicating their superior adaptability to double-row intercropping conditions.

Keywords: agronomic-performance, double-row intercropping, dryland, soybean, variety

INTRODUCTION

Soybeans are a vital secondary crop, valued for their high nutritional content, particularly protein (Kuswantoro *et al.*, 2023). In Indonesia, soybean cultivation predominantly occurs in less productive areas, such as arid regions (Foyer *et al.*, 2019; Wang C. *et al.*, 2020), rain-fed lands (Darré *et al.*, 2019; Haarhoff and Swanepoel, 2021; Rizzo *et al.*, 2022), forested areas, land beneath plantation tress (Mantino *et al.*, 2020; Abeba, 2021), and within intercropping systems (Liu *et al.*, 2017). In West Nusa Tenggara (NTB) province, drylands account for approximately 84% of the agricultural area. To optimise crop productivity, various planting systems, including monoculture and intercropping, have been adopted for diverse agricultural crops (Suhartanto *et al*., 2019; Jaya *et al*., 2022).

In Central Lombok, food crop farming has been advanced through rotational and intercropping practices, which play a crucial role in boosting production on drylands (Maitra *et al*., 2021; Nair *et al*., 2021). Intercropping systems have proven effective in reducing water consumption by 20–50% compared to monoculture systems, presenting a sustainable strategy to improving land and water use efficiency in environments with limited resources (Raza *et al*., 2022).

Previous research has demonstrated that intercropping patterns can enhance land productivity (Temesgen, Fukai and Rodriguez, 2015; Feng *et al*., 2021), improve water use efficiency (Franco, King and Volder, 2018; Liang, He and Shi, 2020), and optimise solar radiation utilisation (Raza *et al*., 2019; Raza *et al*., 2021a). Additionally, several factors influence the intercropping of soybeans and maize, including plant population (Yang *et al*., 2017), plant spacing arrangements (Ren *et al*., 2017; Zheng *et al*., 2022), and the timing of planting seasons (Nirmala, Wangiyana and Farida, 2022; Deng *et al*., 2024; Malcomson, 2024).

Agricultural production in rain-fed dryland areas of Central Lombok faces numerous challenges, including drought stress caused by reduced groundwater and irrigation water availability. Drought stress negatively impacts plant growth (Ahluwalia, Singh and Bhatia, 2021; Seleiman *et al*., 2021) and reduces crop yields (Hemon *et al*., 2018; Suriadi *et al*., 2021; Polakitan, Salamba and Manoppo, 2022). Additionally, studies by Ayu *et al*. (2022) and Sjah *et al*. (2022) highlight that farmers in these areas often have limited knowledge of diverse planting patterns.

The implementation of intercropping using a double-row planting pattern for soybeans and maize provides an efficient land-use strategy to boost crop productivity in dryland regions (Du *et al*., 2018; Blessing *et al*., 2022). This planting method increases plant density by optimising spacing, thereby improving resource utilisation. As a result, farmers can attain higher and more sustainable yields compared to the traditional single-row planting systems. Hemon, Listiana and Dewi (2023) reported that a double-row planting pattern with specific spacing can produce greater pod dry mass than a single-row pattern, leading to an 8.1% yield increase. One of the main challenges in soybean-maize intercropping systems is competition for light (Li *et al*., 2021). The taller growth of maize limits light availability, impacting the quality and amount of light exposure. According to the reports by Ahmed *et al*. (2020) and Pelech *et al*. (2023), soybeans with a more compact plant architecture tend to experience shade stress, resulting from inadequate light quantity and quality, which can impair growth and reduce grain production.

One potential solution to these challenges is the use of soybean varieties that are tolerant to both drought and shade stress, along with suitable intercropping systems (Asghar *et al*., 2020; Cheng *et al*., 2022). Soybean varieties with high productivity, early maturity, desirable taste, and high protein content can thrive when cultivated using agricultural practices suited to the specific land conditions (Li *et al*., 2022). Soybean with high protein content have been developed by the BRIN (National Research and Innovation Agency)of Indonesia (Willis, 2020). These include nine new varieties with protein content around 40%, namely 'Mutiara-1', 'Mutiara-2', 'Mutiara-3', 'Gamasugen-1', 'Gamasugen-2', 'Kemuning-1', 'Kemuning-2', 'Sugentan-1', and 'Sugentan-2'.

This study seeks to assess the agronomic performance of high-protein soybean mutant varieties under different double-row intercropping patterns in the dryland regions of Central Lombok, Indonesia.

MATERIALS AND METHODS

MATERIALS

The study materials consist of five high-protein gamma mutant soybean varieties ('Kemuning-1', 'Mutiara-2', 'Mutiara-3', 'Sugentan-2', 'Gamasugen-2'), a hybrid maize variety ('Nasa 29'), urea, NPK Phonska (12-12-12), and organic fertilisers, and Rudal 25EC insecticide.

METHODS

The experiment was carried out during the dry season (from May to September 2021) in Labulia village, Jonggat sub-district, Lombok, Indonesia. The experimental location (Fig. 1) is

Fig. 1. Map of Labulia Village, experimental location; source: Amrullah, Gaffar and Marsahip (2023)

characterised by lowland topography at an altitude of approximately 41,148 m a.s.l., predominantly vertisol soil, and a rainfall intensity ranging from 1,500–2,500 mm per year. The rainy season typically lasts from November to April, with January being the wettest month (250–350 mm), while the dry season occurs from May to October, with August being the driest (10–30 mm) (Priyono *et al*., 2019). In 2021, however, the study areas experienced precipitation recorded in all months except July which remained dry (Fig. 2). As illustrated in Figure 2, during study period, precipitation levels varied across different months: May (155 mm), June (322 mm), July (0 mm), August (40 mm), and September (65 mm), with the number of consecutive rainy days for these months was 3, 15, 0, 6, and 6 days, respectively. Relative humidity remained relatively stable (82–84%), except in June, when it increased to 87%. Similarly, monthly air temperatures exhibited minimal fluctuations (26–27°C). Solar radiation levels varied considerably throughout the study period, the highest in May, July, and August (84–87%), but declining to 78% in June and 66% in September (BMKG, 2025).

This study employed an experimental method conducted in dryland agricultural areas using split-plot design. The main plot

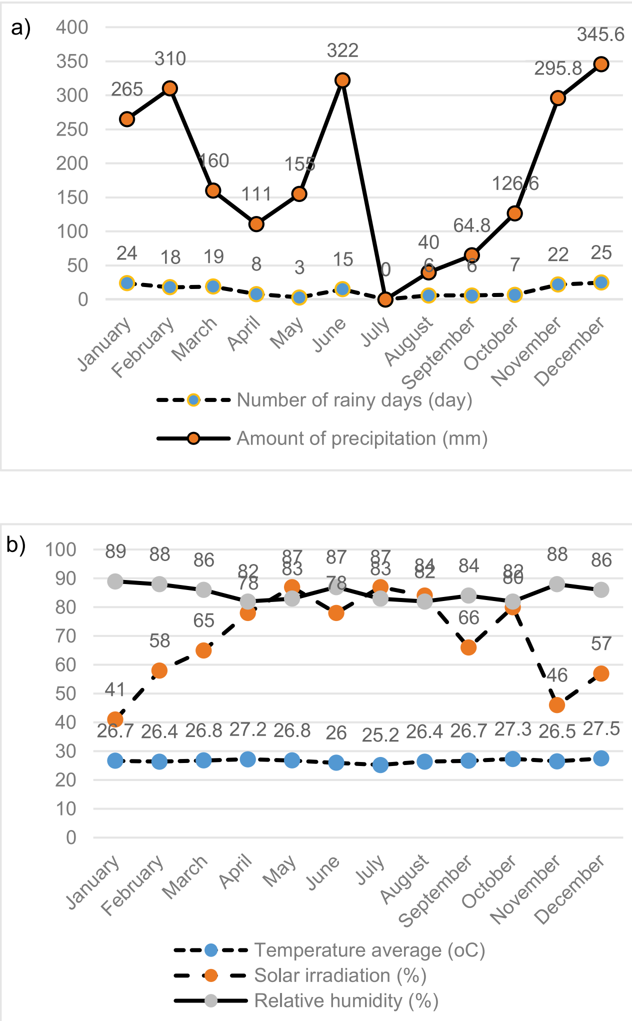

Fig. 2. Climatic conditions during the study period in 2021 in the Jonggat sub-district: a) the number of rainy days and amount of precipitation, b) air temperature, solar irradiation, and relative humidity (BMKG, 2025); own elaboration based on summarised data from monthly report of Kediri Climatology Station

was a double-row soybean-maize intercropping pattern (B) and the subplot was gamma-mutated soybean varieties (V). The main plot (B) included four levels: (B1) double-row soybean sole cropping with 40:20:15 cm spacing (260 plants), (B2) double-row soybean-maize intercropping with 70:20:15 cm spacing (182 soybean plants, 156 maize plants), (B3) double-row soybean-maize intercropping with spacing of 60:20:15 cm (208 soybean plants, 156 maize plants), (B4) double-row soybean-maize intercropping with 50:20:15 cm spacing (208 soybean plants, 208 maize plants). The subplot for gamma mutant soybean varieties (V) includes five varieties: V1 – 'Kemuning-1', V2 – 'Mutiara-2', V3 – 'Mutiara-3', V4 – 'Sugentan-2', V5 – Gamasugen-2'. The characteristics of these varieties are detailed in Table 1. Each combination of the two factors was replicated three times. The arrangement of soybean and maize plants within each row, as well as the spacing between rows in the experimental plots, is illustrated in Figure 3.

Land preparation started by constructing a drainage channel around the experimental plots, measuring 30 cm in depth and 40 cm in width. A total of sixty experimental plots were established, each measuring 4.00 m × 2.85 m (11.4 m^2), and divided into three blocks. Each block contained 20 plots and was separated by a 1 m buffer. Within each block, complete randomisation was applied to all main plots (B), and further randomisation was conducted for the subplots (V) within each main plot (B) (Susilawati, 2015).

Soybean planting was carried out using a drill method, with two seeds sown per hole, two weeks prior to maize planting. Spacing followed the relevant treatment guidelines. Thinning of soybean and maize plants was performed seven days after sowing (DAS), leaving only one healthy plant per hole. Any dead or abnormal plants were replaced.

Soybean and maize were fertilised using urea and NPK Phonska (12-12-12). Soybean fertilisation was applied once at planting, by placing the fertiliser about 5 cm away from each planting hole. A total of 350 g of fertiliser was used per plot, comprising 150 g and 200 g NPK Phonska. For maize, fertilisation was conducted three times with a mixture of urea and NPK Phonska (12-12-12). The first application, carried out 15 days after sowing (DAS), involved 100 g urea and 100 g NPK Phonska per plot, applied by pouring the fertiliser solution 5 cm away from the base of the plants. At 30 DAS, the second fertilisation included 150 g urea and 100 g NPK Phonska per plot. At 60 DAS, the third application consisted of 150 g urea and 200 g NPK Phonska per plot, also applied by sowing.

Weeding was done by removing undesirable plants surrounding the crops, conducted twice at 21 and 35 DAS. Pest insects management was conducted intensively, utilising both mechanical and chemical methods, with careful selection of pesticide types based on control requirements. Pest insect control was conducted using Rudal 25EC insecticide at the recommended dosage. Irrigation was adjusted based on the land conditions, as the land remains wet due to rainfall from May to June. The irrigation was applied once at 60 DAS.

Soybean harvest dates depended on the soybean variety. For 'Sugentan-2' and 'Gamasugen-2' varieties, harvesting was performed at 85 DAS, whereas for 'Kemuning-1', 'Mutiara-2', and 'Mutiara-3' varieties it took place at 110 DAS. Meanwhile, maize was harvested at 127 DAS.

Table 1. Characteristics of five gamma mutant soybean varieties used in this study

Gamma mutant soybean variety	Characteristics
'Kemuning-1'	A new high-yield soybean variety developed by the National Research and Innovation Agency derived from Panderman variety enhanced through gamma radiation, released in 2019, high productivity (2.87 $Mg \cdot ha^{-1}$), high protein content (39.49%), yellow and large grain variety, a medium growth period (flowering 34.16 DAS, maturing 79–80 DAS), drought resistance. Name of Kemuning is an abbreviation for drought-resistant mutant soybeans (Ind.: kedelai mutan tahan kekeringan).
'Mutiara-2'	A high-yield soybean variety developed by the National Research and Innovation Agency (BRIN) derived from 'Cikuray' variety enhanced through gamma radiation, released in 2014, high productivity (2.4 $Mg \cdot ha^{-1}$), high protein content (38.4%), black and large grain variety, a medium growth period (flowering 35 DAS, maturing 87 DAS), resilience against pests and diseases.
'Mutiara-3'	A high-yield soybean variety developed by the National Research and Innovation Agency (BRIN) of Indonesia derived from 'Cikuray' variety enhanced through gamma radiation, released in 2014, high productivity (2.4 $Mg \cdot ha^{-1}$), high protein content (38.5%), black and large grain variety, a medium growth period (flowering 35 DAS, maturing 84 DAS), resilience against pests and diseases.
'Gamasugen-2'	A new high-yield soybean variety developed by the National Research and Innovation Agency (BRIN) of Indonesia derived from 'Tidar' variety, enhanced through gamma radiation treatment, released in 2013, high productivity (2.4 $Mg \cdot ha^{-1}$), moderate protein content (37.4%), yellow and moderate grain variety, a very short growth period (flowering 30 DAS, maturing 68 DAS), resilience against pests and diseases.
'Sugentan-2'	A new high-yield soybean variety developed by the National Research and Innovation Agency (BRIN) derived from 'Argomulyo' variety, enhanced through gamma radiation, released in 2021, high productivity (2.7 $Mg \cdot ha^{-1}$), high protein content (40.24%), yellow and small grain variety, a very short growth period (flowering 32 DAS, maturing 67 DAS), resilience against pests and diseases.

Explanation: DAS = days after sowing.
Source: own elaboration.

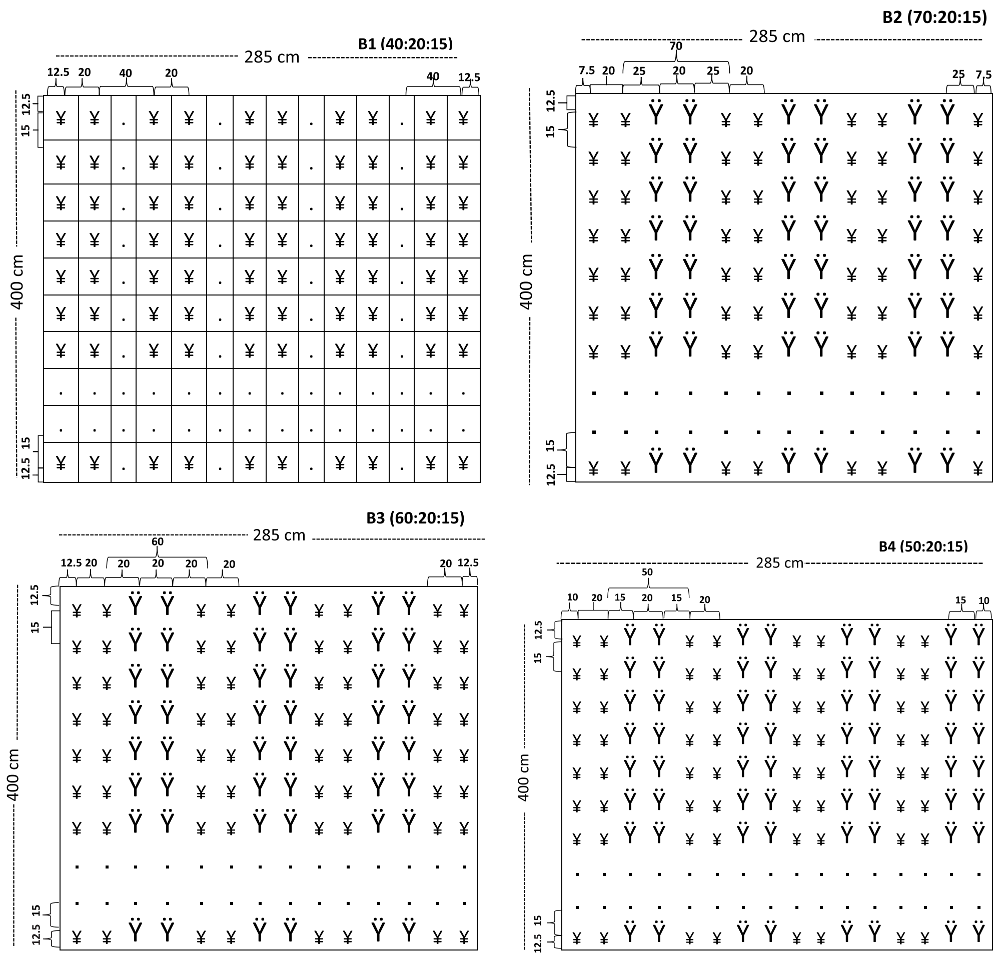

Fig. 3. The diagrammatic position of soybean (¥) and maize (Ÿ) plants in each row and the distance between rows in the experimental plots; source: own elaboration

The number of sample plants for each variable observed in soybean was set at 5% of the population, resulting in 13, 9, 10, and 12 sample plants for B1, B2, B3, and B4, respectively. Agronomic traits recorded at 60 DAS and included plant height (cm), trifoliate leave number (leaves), trifoliate leaf area (cm^2), node number (nodes), and branch number (branches). Days to flowering were recorded based on the first appearance of flowers on each sample plant, number of grains, 100-grain mass (g), grain mass per plant (g), and grain yield (Mg·ha^{-1}), which was calculated based on the soybean population per treatment. Additionally, the partial land equivalent ratio (*pLER*) was also calculated to determine the suitable soybean variety for the intercropping system, using Equation (1) (Mead and Willey, 1980).

$$pLER = \frac{YIS}{YS}\ 100\% \tag{1}$$

where: *YIS* = yield of intercropped soybean, *YS* = yield of sole cropped soybean.

The data were analysed using the analysis of variance (ANOVA), and mean comparisons were conducted using the Tukey (HSD) test with a 5% significance level. These statistical analyses were performed using the SmartStatXL software.

RESULTS AND DISCUSSION

RESULTS

The analysis of variance results, summarised in Table 2, show that the B×V interaction had a significant impact on the number of nodes, branches, pods, filled pods, as well as percentage of unfilled pods, grain number, grain mass per plant, and grain yield per hectare. The soybean variety (V) significantly affected all observed variables, while the double-row soybean-maize intercropping pattern (B) significantly affected only the number of nodes and branches, days to flowering, and grain yield per hectare.

The impact of the B×V interaction on various traits, including the number of nodes, branches, pods, filled pods, %-unfilled pods, grain number, grain mass per plant, and grain yield per hectare, are shown in Figure 4. The simple effects of the B×V interaction can be analysed by comparing the same variety across different intercropping patterns and by comparing different varieties within the same intercropping pattern. As for the number of nodes and branches during the vegetative growth period, as depicted in Figure 4a and 4b, the double-row intercropping (B2–B4) negatively affected the 'Mutiara-2') and 'Gamasugen-2'. The highest node number of 'Mutiara-2' (20.2 nodes) in the double-row monoculture soybean (B1) significantly decreased in the wider double-row intercropping (B2) but remained unchanged in the narrower spacings of B3 and B4. The node number of 'Gamasugen-2' remained relatively the same, with a slight increase in B3 and B4. In contrast, 'Kemuning-1' showed no notable variation across the double-row intercropping patterns, displaying similar performance to 'Mutiara-3' and 'Sugentan-2'. Within the double-row intercropping (B), 'Mutiara-2' had the highest node number in B1, while 'Mutiara-2' had the lowest. 'Mutiara-3' showed the highest node number in B2 and B3, whereas 'Kemuning-1' and 'Gamasugen-2' had the highest values in B4.

Regarding the number of branches, 'Mutiara-3' and 'Mutiara-2' displayed a higher branch number in B1 and B2, but significantly lower in B3 and B4. In contrast, 'Kemuning-1' had a higher branch number in B2 than in B1, B3, and B4. Among the B's, 'Mutiara-3' had the highest branch number in B1, while 'Kemuning-1' and 'Mutiara-3' had the most branches in B2. 'Mutiara-2' had the fewest branches in B3, while in B4,

Table 2. The agronomic trait performance of soybean varieties in different double-row soybean-maize intercopping configurations

Variable	Mean square				*CV* (%)
	block	double-row (B)	variety (V)	interaction B×V	
Plant height (cm)	20.960^{ns}	9.571^{ns}	539.977***	17.074 ^{ns}	12.936
Trifoliate leaf number	2.816^{ns}	3.760^{ns}	49.940***	5.814 ^{ns}	28.286
Trifoliate leaf area (cm^2)	253.690^{ns}	1484.938^{ns}	7914.716***	146.831^{ns}	17.393
Node number	30.032*	38.170*	13.731***	8.829***	7.453
Branch number	0.643*	1.489**	0.371***	0.209***	6.834
Days to flowering (DAS)	11.017^{ns}	53.022**	30.775*	6.675^{ns}	10.531
Pod number	41.162*	7.621^{ns}	375.485***	16.106*	7.611
Filled pod number	23.508^{ns}	4.173^{ns}	435.075***	20.509**	7.265
%-unfilled pod number (%)	17.518^{ns}	34.386^{ns}	130.719***	14.802**	23.442
Grain number per plant	60.638^{ns}	20.200^{ns}	1905.826***	76.597**	7.703
100 grain mass (g)	2.128^{ns}	0.013^{ns}	279.545***	0.284^{ns}	5.305
Grain mass per plant (g)	0.075^{ns}	0.117^{ns}	0.463***	0.463***	4.376
Grain yield (Mg·ha^{-1})	0.003^{ns}	0.570***	0.470***	0.032***	4.473

Explanations: ns = no significant difference; *, **, *** = significant difference at $p \leq 0.05$, $p \leq 0.01$, $p \leq 0.001$ level subsequently; *CV* = coefficient of variation.
Source: own study.

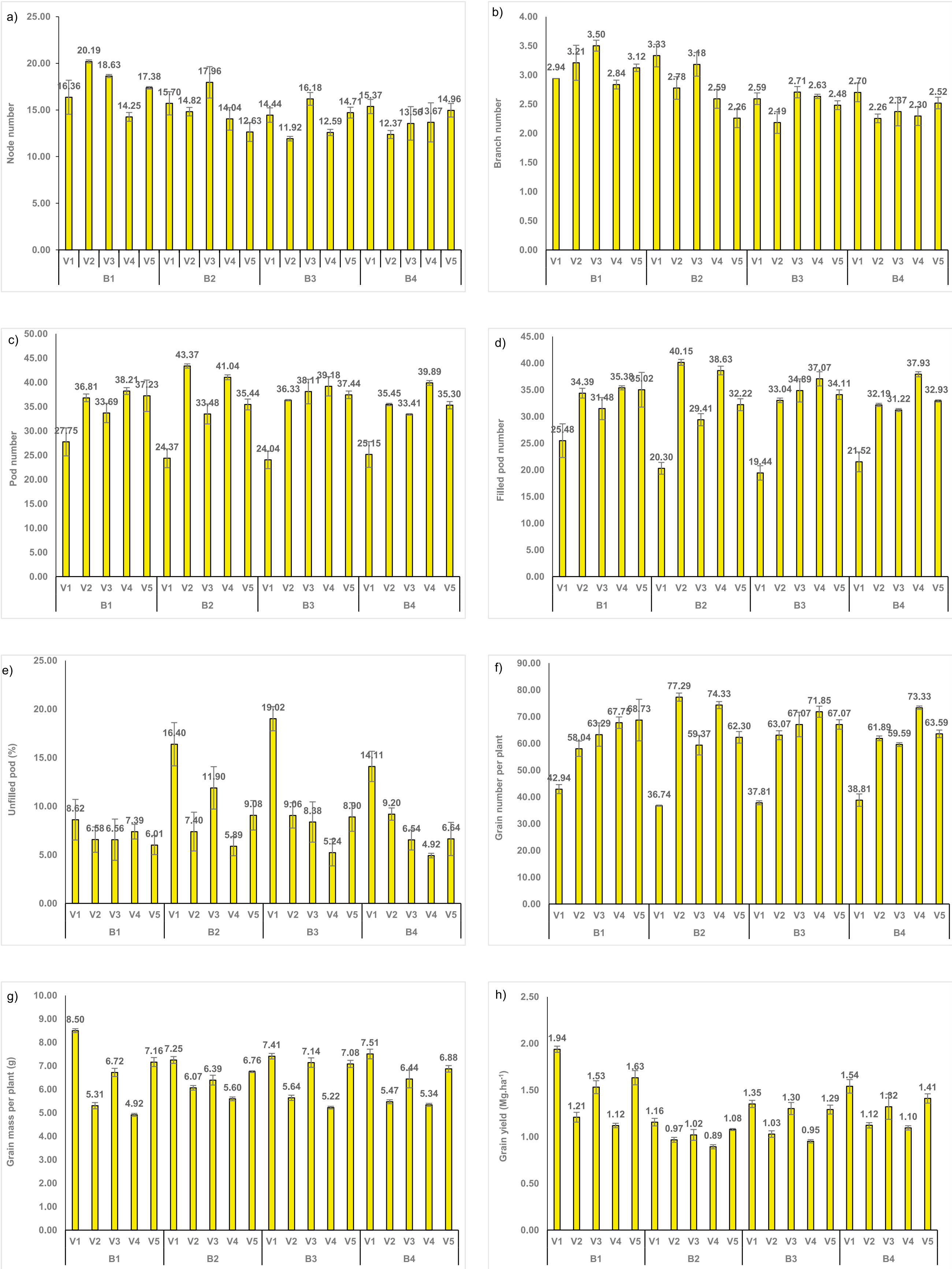

Fig. 4. Interaction effects of double-row soybean-maize intercropping pattern (B) and the subplot was gamma-mutated soybean varieties (V) on the: a) node number, b) branch number, c) pod number, d) filled pod number, e) %-unfilled pod number, f) grain number per plant, g) grain mass per plant, h) grain yield per hectare; source: own study

'Kemuning-1' had more branches than both 'Mutiara-2' and 'Sugentan-2'.

The B×V interaction significantly influenced various agronomic traits during the generative growth period of soybean, including pod number, filled pod number, %-unfilled pods, grain number, grain mass per plant, and grain yield per hectare (Tab. 2). As shown in Figures 4c–f, the B×V interaction notably influenced the number of pods, filled pods, percentage of unfilled pods, grain number, particularly in 'Mutiara-2' and 'Sugentan-2'. In both varieties, these three variables significantly increased under the wider spacing double-row intercropping (B2) compared to the soybean sole cropping system (B1). The number of pods and grains of 'Mutiara-2' significantly decreased in the closer double-row intercropping of B3 and B4, but showed no difference in the B1, while Sugentan-2 maintained a higher and unchanged number than the others. 'Kemuning-1' had the fewest pods, filled pods, and grains compared to the other varieties in all intercropping patterns. Regarding the percentage of unfilled pods, 'Kemuning-1' saw a significant increase in both the wider spacing double-row intercropping (B2) and the narrower intercropping B3 and B4 (Fig. 4e).

A highly significant effect of the B×V interaction was observed for both grain mass per plant and grain yield (Tab. 2). This interaction revealed that under soybean sole cropping (B1), 'Kemuning-1' had the highest grain mass and yield, with 8.50 g per plant and 1.94 $Mg \cdot ha^{-1}$, respectively. However, there was a considerable decline in both parameters under double-row soybean-maize intercropping patterns (B2, B3, B4). Despite this, 'Kemuning-1' maintained a relatively high grain mass per plant, ranging from 7.25 to 7.51 g, and grain yields from 1.16 to 1.54 $Mg \cdot ha^{-1}$ in these intercropping patterns (Fig. 4g–h). In other words, 'Kemuning-1', 'Mutiara-3', and 'Gamasugen-2' consistently had higher grain mass per plant and grain yield compared to 'Mutiara-2' and 'Sugenta-2' both in sole cropping and intercropping systems. In contrast, 'Mutiara-2' and 'Sugentan-2' showed a slight increase in grain mass and grain yield under double-row intercropping systems (B2, B3, and B4) compared to sole cropping (B1). Nevertheless, as revealed in Figures 4g and 4h, these two varieties still exhibited the lowest grain mass (5.31–6.07 and 4.92–5.60 g, respectively) and grain yield (0.97–1.12 and 0.89–1.10 $Mg \cdot ha^{-1}$, respectively) across all double-row intercroppings.

In addition to the interaction effects, the main factors of soybean variety (V) and double-row intercropping (B) influenced the agronomic trait performance. Soybean variety (V) had a significant effect on plant height, number of trifoliate leaves, and trifoliate leaf area (Tab. 3), as well as on days to flowering and 100-grain mass (Tab. 4). As shown in Table 3, 'Kemuning-1' exhibited the highest plant height (43.70 cm), followed by 'Mutiara-3', 'Gamasugen-2', 'Sugentan-2', with the lowest plant height observed in 'Mutiara-2' (26.76 cm). 'Mutiara-3', 'Kemuning-1', and 'Gamasugen-2' had the highest number of trifoliate leaves), while 'Sugentan-2' and 'Mutiara-2' had the lowest number. Similar trends were observed in trifoliate leaf area, 'Mutiara-3', 'Gamasugen-2', and 'Kemuning-1' having the largest leaf areas, while 'Mutiara-2' and 'Sugentan-2' showing the smallest leaf areas.

The performance of days to flowering and 100-grain mass resulting from both the single variety factor and double-row intercropping patterns, is shown in Table 4.

As presented in Table 4, the days to flowering in the double-row soybean-maize intercropping patterns (B) revealed that the shortest time to flowering was observed in the narrowest spacing of intercropping pattern B4 (50:20:15 cm) at 25.73 DAS. Moreover, when considering the soybean varieties individually, the earliest flowering occurred in 'Mutiara-2' at 26.42 DAS, while the latest flowering was in 'Mutiara-3' at 30.33 DAS, followed by

Table 3. The performance of agronomic traits during the vegetative growth period of soybeans in various double-row intercropping patterns in the dryland of Central Lombok, Indonesia

Treatment	Plant height (cm)	Trifoliate leaf number	Trifoliate leaf area (cm^2)	Node number	Branch number
B (double-row soybean-maize intercropping patterns)					
B1	31.777^{a}	9.255^{a}	109.330^{a}	17.361^{a}	3.123^{a}
B2	32.348^{a}	8.207^{a}	119.986^{a}	15.031^{ab}	2.829^{ab}
B3	31.571^{a}	8.253^{a}	101.147^{a}	13.969^{b}	2.521^{bc}
B4	33.355^{a}	8.830^{a}	122.725^{a}	13.986^{b}	2.430^{c}
HSD 0.05	5.798	3.511	30.547	2.686	0.330
V (soybean varieties)					
V1	43.698^{a}	10.024^{a}	128.365^{a}	15.468^{ab}	2.893^{a}
V2	26.758^{c}	5.953^{b}	87.017^{b}	14.825^{bc}	2.608^{b}
V3	31.892^{b}	10.405^{a}	135.892^{a}	16.583^{a}	2.942^{a}
V4	28.189^{bc}	6.938^{b}	83.677^{b}	13.638^{c}	2.590^{b}
V5	30.777^{bc}	9.863^{a}	131.536^{a}	14.920^{bc}	2.597^{b}
HSD 0.05	4.923	2.881	23.243	1.326	0.220

Explanations: numbers followed by the same letter in the same column and treatment indicate no significant difference at the 0.05 Tukey's test; B1 = single-row soybean sole cropping in a spacing of 40:20:15 cm; B2 = double-row soybean-maize intercropping patterns in a spacing of 70:20:15 cm; B3 = double-row soybean-maize intercropping patterns in a spacing of 60:20:15 cm; B4 = double-row soybean-maize intercropping patterns in a spacing of 50:20:15 cm; V1 = 'Kemuning-1', V2 = 'Mutiara-2', V3 = 'Mutiara-3', V4 = 'Sugentan-2', V5 = 'Gamasugen-2'.
Source: own study.

Table 4. The performance of agronomic traits during the generative growth of soybeans in double-row soybean-maize intercropping patterns in the dryland of Central Lombok, Indonesia

Treatment	Days to flowering (DAS)	Pod number	Filled pod number	Unfilled pod number (%)	Grain number	100 grain mass (g)	Grain mass (g·plant^{-1})	Grain yield (Mg·ha^{-1})
B (double-row soybean-maize intercropping patterns)								
B1	28.73^{a}	34.74^{a}	32.35^{a}	7.03^{a}	60.15^{a}	11.49^{a}	6.52^{a}	1.49^{a}
B2	29.80^{a}	35.54^{a}	32.14^{a}	10.13^{a}	62.01^{a}	11.43^{a}	6.41^{a}	1.02^{d}
B3	29.60^{a}	35.02^{a}	31.71^{a}	10.12^{a}	61.38^{a}	11.43^{a}	6.50^{a}	1.19^{c}
B4	25.73^{b}	33.84^{a}	31.16^{a}	8.28^{a}	59.44^{a}	11.43^{a}	6.33^{a}	1.30^{b}
HSD 0.05	2.37	2.97	3.40	5.46	5.79	1.02	0.26	0.05
V (soybean varieties)								
V1	29.58^{ab}	25.33^{c}	21.69^{d}	14.54^{a}	39.08^{c}	19.66^{a}	7.67^{a}	1.30^{a}
V2	26.42^{b}	37.99^{a}	34.94^{ab}	8.06^{bc}	65.07^{b}	8.62^{c}	5.62^{c}	1.08^{c}
V3	30.33^{a}	34.67^{b}	31.75^{c}	8.35^{b}	62.33^{b}	10.85^{b}	6.67^{b}	1.29^{b}
V4	27.33^{ab}	39.58^{a}	37.25^{a}	5.86^{c}	71.82^{a}	7.34^{d}	5.27^{d}	1.02^{d}
V5	28.67^{ab}	36.35^{ab}	33.57^{bc}	7.66^{bc}	65.42^{b}	10.76^{b}	6.97^{b}	1.35^{b}
HSD 0.05	3.54	3.30	2.73	2.46	5.52	0.72	0.33	0.07

Explanations: numbers followed by the same letter in the same column and treatment indicate no significant difference at the 5% Tukey's test; B1, B2, B3, B4 = as in Tab. 3; V1, V2, V3, V4, V5 = as in Tab. 3.
Source: own study.

'Kemuning-1', 'Gamasugen-2', and 'Sugentan-2'. The 100-grain mass varied across varieties, with the heaviest grains from 'Kemuning-1' at 19.66 g, followed by 'Mutiara-3' and 'Gamasugen-2', and 'Mutiara-2', while 'Sugentan-2' had the lightest grains at 7.34 g. The 100-grain mass of 'Kemuning-1' was nearly three times that of 'Sugentan-2' and 'Mutiara-2', and almost twice as high as 'Mutiara-3' and 'Sugentan-2'.

Table 5 indicates that although the grain yields of 'Kemuning-1', 'Mutiara-3', and 'Gamasugen-2' were higher than that of 'Mutiara-2' and 'Sugentan-2' in all cropping system (B1, B2, B3, and B4), the partial land equivalent ratio (*pLER*) values showed the opposite trend. The *pLER* values of 'Mutiara-2' (80–93%) and 'Sugentan-2' (80–98%) were higher than those of 'Kemuning-1' (60–80%), 'Mutiara-3' (67–86%), and 'Gamasugen-2' (66–86%).

Table 5. Partial land equivalent ratio (*pLER*) of soybean varieties under double-row intercropping patterns in the dryland region of Central Lombok, Indonesia

Variety	Grain yield per hectare (Mg·ha^{-1})				Partial land equivalent ratio (%)		
	B1	B2	B3	B4	B2	B3	B4
V1	1.94	1.16	1.35	1.54	59.72	69.76	79.51
V2	1.21	0.97	1.03	1.12	80.02	85.04	92.83
V3	1.53	1.02	1.30	1.32	66.60	85.01	86.29
V4	1.12	0.89	0.95	1.10	79.69	84.95	97.74
V5	1.63	1.08	1.29	1.41	66.02	79.10	86.39

Explanations: B1, B2, B3, B4 = as in Tab. 3; V1, V2, V3, V4, V5 = as in Tab. 3.
Source: own study.

Varieties 'Mutiara-2' and 'Sugentan-2' consistently demonstrated high *pLER* values across all intercropping treatments, with values reaching up to 98% for 'Sugentan-2' on B4. In contrast, 'Kemuning-1' showed comparatively lower *pLER* values, with a gradual increase from 60% (B2) to 80% (B4). 'Mutiara-3' and 'Gamasugen-2' showed moderate performance with *pLER* values ranging from mid-60s to mid-80s. Therefore, the 'Mutiara-2' and 'Sugentan-2' varieties were found to be more suitable or better adapted to the double-row soybean-maize intercropping systems compared to 'Kemuning-1', 'Mutiara-3', and 'Gamasugen-2'.

DISCUSSION

The intercropping system involves planting two or more crop species together on the same land to enhance land utilisation and boost crop yield (Raza *et al.*, 2021b; Raza *et al.*, 2023). The intercropping of soybeans and maize can be implemented through different methods, including row planting patterns (Feng *et al.*, 2019; Raza *et al.*, 2019), alley planting (Mantino *et al.*, 2020; Luo *et al.*, 2023), mixed planting (Iqbal *et al.*, 2019), and zigzag planting (Slameto *et al.*, 2024). These methods take advantage of the specific nutritional requirements, light, water, and growth durations of each species (Glaze-Corcoran *et al.*, 2020; Yang *et al.*, 2021). Furthermore, intercropping methods can support pest and disease control, as diversifying crops reduces the likelihood of severe pest infestations compared to monoculture systems (Chadfield, Hartley and Redeker, 2022; Mir *et al.*, 2022).

Different soybean varieties display unique growth patterns, resulting in differences in plant height, number of trifoliate leaves, and leaf area (Tab. 3), as well as days to flowering and 100-grain mass (Tab. 4). The soybean variety has a significant impact on plant height due to genetic variations and growth habits. The results of this study are in line with what was reported by Purba, Suswati and Noer (2024), who observed that particular varieties show unique growth patterns. Varieties producing greater number of trifoliate leaves may improve overall plant vitality because the number of trifoliate leaves serves as a crucial indicator of a plant's photosynthetic efficiency and growth potential. Likewise, varieties with larger leaves are likely to generate more biomass and yield since the leaf area is closely tied to the plant's capacity to absorb sunlight for photosynthesis. Selecting soybean varieties with ideal plant height, number of trifoliate leaves, and leaf area may result in enhanced growth rates and overall productivity.

The days to flowering among soybean varieties varied across different double-row spacing (Tab. 4), indicating that the trait was influenced by environment conditions. The shortest time to flowering was observed in the narrowest spacing treatment (B4) of the double-row intercropping system. This indicates that soybeans grown under narrower spacing experienced shading stress from maize, triggering soybeans to expedite the transition from the vegetative to generative phase as an adaptive strategy to ensure reproduction under resource-limited environmental conditions (Feng *et al*., 2019; Raza *et al*., 2022).

The 100-grain mass varied significantly among soybean varieties (Tab. 4). 'Kemuning-1' (V1) revealed the highest 100-grain mass and outperforming all other varieties. This variability is largely influenced by genetic factors. 'Kemuning-1' also recorded the highest grain yield per hectare and per plant, along with the highest 100-grain mass, despite having the lowest number of grains per plant. These findings highlight the critical role of 100-grain mass in determining overall plant grain yield. These results align with Razi, Nura, and Zuyasna (2022), who also reported that 'Kemuning-1' had the highest 100-grain mass among the tested varieties. Additionally, 'Kemuning-1' consistently achieved the highest grain yields per plant and per hectare across various intercropping patterns.

The B×V interaction had a significant impact on various agronomic traits during both the vegetative (Fig. 4a–b) and generative growth stages of soybeans (Fig. 4c–h). These differences are likely attributable to factors such as improved light interception, enhanced water use efficiency, and optimised nutrient availability due to the complementary interaction between the two crops. The double-row planting pattern promotes more efficient utilisation of space and resources, thereby playing a key role in maximising agricultural productivity within sustainable farming systems (Raza *et al*., 2022; Zhou *et al*., 2024).

The number of nodes and branches in soybean determines plant architecture and yield potential. In this study, those traits decreased under narrower spacing in soybean-maize intercropping (Tab. 3; Fig. 4a–b). This decline is likely due to intensified competition for light, water, and nutrients among closely spaced plants, which restricts individual plant growth and development (Harsono *et al*., 2020; Li, Chen and Xing, 2022). Ren *et al*. (2021) also noted that maize tend to grow taller, potentially overshadowing soybean plants and limiting the soybeans' photosynthetic capacity. This effect may result in fewer nodes and branches as soybean adjust to the reduced light availability. Therefore, choosing suitable varieties for specific intercropping can enhance yields and improve resource use efficiency, minimising competition stress, and promoting favourable morphological traits like increased number of nodes and branches. Certain high-yielding soybean varieties may sustain or even enhance their number of nodes and branches when grown in intercropping, as they exhibit superior adaptability to competitive environments compared to other varieties (Wang X. *et al*., 2020).

Yield is largely influenced by the number of pods produced (AIshwany and Ali, 2024). This study revealed significant differences in the number of pods among soybean varieties grown under intercropping conditions (Tab. 4; Fig. 4). These differences highlight the importance of selecting appropriate genotypes to maximise yield in intercropping systems. The percentage of unfilled pods also serves as an indicator of plant stress or resource competition in such environments. Improved light interception and efficient resource use in intercropping systems associate with a lower percentage of unfilled pods, reflecting improved plant health and resource allocation (Porte *et al*., 2022).

The B×V interaction significantly affected both the grain mass and yield (Tab. 2). These traits exhibit variable patterns depending on the row configurations, indicating that soybeans may thrive under specific conditions but could experience a decline in yield when planted in denser arrangements due to heightened competition within the species (Zhang *et al*., 2015; Khalid *et al*., 2023). As shown in Table 4 and Figure 4h, the varieties 'Kemuning-1', 'Mutiara-3', and 'Gamasugen-2' exhibited higher mean grain yields compared to 'Mutiara-2' and 'Sugentan-2' across both sole cropping and intercropping systems. This suggests that these three varieties are high-yielding even at close planting distance. These results indicate the presence of genetic factors and the impact of the interaction or complementary effect between soybean and maize (Feng *et al*., 2022; Raza *et al*., 2022).

The grain yield of the three high-yielding varieties ('Kemuning-1', Mutiara-3, and 'Gamasugen-2') exhibited a more pronounced decline under intercropping conditions (Fig. 4h). This reduction was with an increased proportion of unfilled pods (Fig. 4e), a reduction in the number of filled pods (Fig. 4d), and a decrease in grain mass per plant (Fig. 4g). These findings suggest that 'Kemuning-1, 'Mutiara-3', and 'Gamasugen-2' are more susceptible to competition or stress in intercropping systems compared to 'Mutiara-2' and 'Sugentan-2'. This observation study suggests that these high-yielding varieties may not be as efficient or adaptable in double-row intercropping systems, as they experience more significant yield losses when grown alongside other species. In contrast, while 'Mutiara-2' and 'Sugentan-2' consistently exhibit lower mean grain yields in both sole cropping and intercropping, the two varieties increase their grain number and grain mass per plant, and they maintain more stable grain yield in both conditions. Notably, 'Mutiara-2' and 'Sugentan-2' demonstrated higher partial land equivalent ratios (*pLER*) (Tab. 5), which suggests that, relative to their grain yield, they these two varieties performed more effectively in double-row intercropping systems compared to 'Kemuning-1', 'Mutiara-3', and 'Gamasugen-2'. This higher *pLER* indicates that although 'Mutiara-2' and 'Sugentan-2' have lower grain yields, they are more efficient competitors adaptable in intercropping systems. Consequently, 'Mutiara-2' and 'Sugentan-2' may be better suited for double-row intercropping due to their ability to experience less yield loss under competition, thereby utilising available resources more effectively in such systems. These results highlight the significance of choosing suitable planting systems, spacing, and varieties to enhance soybean growth (Feng *et al.*, 2021; Raza *et al.*, 2022; Munz *et al.*, 2025).

Double-row soybean-maize intercropping is a sustainable farming method that can result in increased yield, better resource use, and greater economic benefits for farmers. By planting two rows of crops in the same space, land-use efficiency is improved. This strategy can raise the plant population by up to 45%, ultimately increasing the yield per unit of land (Lewar, Hasan and Vertygo, 2023).

The double-row planting intercropping method reduces the likelihood of crop failure by providing a buffer – if one crop fails, the other can still yield successfully. This strategy enables farmers to attain a more significant overall financial gain. Furthermore, the system promotes soil fertility and biodiversity, while also preventing soil erosion (Moreira *et al.*, 2024). Ensuring proper spacing in a double-row intercropping can greatly improve resource utilisation efficiency among plants. This intercropping maximises the use of light, water, and nutrients while reducing plant competition (Zhou *et al.*, 2020).

CONCLUSIONS

The interaction between the double-row soybean-maize intercropping system and soybean variety significantly impacted the agronomic traits, such as the number of nodes and branches, grain yield, and related components. The varieties 'Kemuning-1', 'Mutiara-3', and 'Gamasugen-2' performed better in a sole cropping system. The consistent yield stability of 'Mutiara-2' and 'Sugentan-2' showed greater efficiency in double-row intercropping systems. The consistent yield stability of 'Mutiara-2' and 'Sugentan-2' across both sole and double-row intercropping systems indicates their superior adaptability to double-row intercropping conditions. Yields produced by 'Kemuning-1', 'Mutiara-3', and 'Gamasugen-2' were more significantly reduced in intercropping, suggesting lower adaptability to the system.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interest.

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