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Growth and Yield Performance of Two Contrasting Mung Bean Varieties Under Varying Plant Population Densities

Ezzat Abd El Lateef*, Mostafa Selim, Mostafa Abd El- Salam, Mohamed Nowar, Abd elazeem Salem

Field Crops Research Department, Agricultural and Biological Research Institute, National Research Centre, 33 El-Buhouth Street, Giza, Egypt.

*Corresponding author: profabdellateef@gmail.com

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ABSTRACT: Mung bean is a promising crop in Egypt, but the small seed size (≤ 4 g) of high-yielding varieties like Kawmy-1 limits its widespread adoption. Larger-seeded varieties with higher yield potential, such as VC1973 A (100-seeds > 4 g), are preferred by farmers. However, the impact of plant population densities on growth and yield of these contrasting varieties has not been well studied. This research was conducted during the 2023 and 2024 in summer seasons, aimed to evaluate the effects of varying plant population densities (75, 150, 225, and 300 thousand plants per fed, equivalent to 4200 m^2) on the growth, yield, and physiological responses of two mung bean varieties, Kawmy-1 and VC1973 A, under biological stress. The results revealed that Kawmy-1 exhibited tolerance to high-density stress (300,000 plants per fed), maintaining favorable growth and yield, while VC1973 A showed superior vegetative growth across parameters such as dry matter accumulation, leaf area, and leaf weight ratio. In contrast, Kawmy-1 excelled in attributes like leaf area ratio, specific leaf area, relative growth rate, and net assimilation rate. Increased plant density significantly reduced several growth parameters, but some traits like leaf area index, leaf area ratio, and leaf weight ratio showed reversible trends. In terms of yield, Kawmy-1 outperformed VC1973 A in pod and seed yield plant^{-1}, while VC1973 A achieved better plant height and 100-seed weight. Interestingly, higher plant densities enhanced protein content but decreased overall yield and carbohydrate levels. This study underscores the importance of optimizing plant population density to balance yield and quality in mung bean cultivation. Future research should explore the genetic potential of larger-seeded varieties like VC1973 A, as well as strategies to enhance their performance under varying agronomic conditions.

KEYWORDS: Mung bean varieties, biological stress, growth, plant density, yield, chemical content

1. Introduction

Mung bean (*Vigna radiata* (L.) is a pulse crop that can be grown under marginal conditions with limited moisture and low soil fertility (Rana et al., 2011). Pulses are known as poor man's meat and a cheap source of vegetable protein containing 20-25% protein (Ghotbi et al., 2022). The mung bean (*Vigna radiata* (L.) Wilczek) is esteemed among the entire pulse species because it is an easily digestible pulse (Imran et al., 2016). Mung bean (*Vigna radiata* (L.) Wilczek) is highly regarded among all pulse species due to its ease of digestion and its use in different rotations and intercropping systems, as well as it offers a clear advantage over other longduration summer legumes (Kabir et al., 2010). It is characterized with high nutritive value, 1.3% fat, 60.4% carbohydrate, 4% mineral, and 3% vitamins, and is rich in essential amino acids specifically lysine, which is deficient in most cereal grains (Kabir, and Sarkar, 2008, Miah et al., 2009, Hussain et al., 2011, Mondal et al., 2012; Chauhan, and Williams, 2018). Additionally, mung bean can also be grown twice a year, i.e., in the spring and autumn seasons, which gives it the potential to act as green manure or feed for livestock (Bhardwaj et al., 1999; Kumar, et al., 2013).

Despite these benefits, mung bean cultivation faces several challenges. One major issue is the limited widespread adoption of mung beans in Egypt, attributed to the small seed size of high-yielding cultivars like Kawmy-1. Although small-seeded genotypes outperform larger-seeded ones in yield per hectare, large-seeded genotypes with high yield potential are still preferred (Abd El Lateef et al., 2019). Furthermore, the physiological performance of mung bean cultivars in Egypt, especially under varying plant population densities, is not well understood. Numerous studies have investigated agronomic techniques to enhance mung bean productivity in Egypt (Abd El-Salam et al., 2008; Abd El Lateef et al., 2020). Additionally, genetic variability among mung bean entries, including the Egyptian local registered variety, has been identified (Mohamed et al., 2005; Abd El Lateef et al., 2020). The crop is also valuable as both a seed and fodder source due to its high biomass production and ability to recover from grazing while maintaining high seed yields (Abd El Lateef et al., 2020). The performance of mung bean growth, yield, and its components has been extensively studied. For example, Kumar et al. (2013) examined the physiological response, growth, and yield of four mung bean varieties under various water-logging conditions. Mondal et al., (2011b) proposed that yield components depend on specific physiological traits and that seed rate is closely related to biomass, yield, and the number of pods per plant.

The physiological performance of mung bean cultivars in Egypt at both normal and high plant population densities is not well understood. Thus, the purpose of this study is to identify the performance of mung bean growth, yield and quality under varying plant population densities in sandy soil.

2. Materials and methods

2.1. Experimental site

During the summer seasons of 2023 and 2024, two field experiments were conducted at the Experimental Farm, National Research Centre El-Behaira Governorate, Egypt (30.30° N, 30.18° E and 21 m above sea level). The experimental soil was sandy with a pH and EC of 0.38 and 8.2 dS m^{-1}, respectively. The basic soil chemical properties of the experimental site are presented in Table (1).

2.2. Experimental design and treatments

The experiments were conducted in split – plot design in the summer seasons of 2023 and 2024. The treatments included two mung bean varieties (Kawmy-1 and VC1973 A) and four plant population densities (75, 150, 225 and 300 thousand plants fed^{-1}., respectively). The large seed variety VC1973 A was imported from the Asian-Vegetable Research for Development Centre (AVRDC), evaluated and adapted in Egypt while the variety Kawmy-1 was developed and registered by the by Field Crops Research Department, National Research Centre, Egypt. The plots were arranged in a split-plot design with four replicates, in which varieties were allocated, to the main plots and plant population densities the sub-plots. Each sub-plot consisted of 6 ridges, 60 cm apart and 4 meters long and the plot area was (14.4 m^2). The sowing date was in the first week of May in both seasons.

Phosphorous fertilization at 150 kg fed^{-1} level as calcium supper phosphate (15.5% P_2O_5) and 100 kg fed^{-1} potassium sulfate (48% K_2O) were applied during soil preparation, while 15 kg N fed^{-1}. as ammonium sulfate (206% N) was applied after sowing and before the second irrigation. A specific rhizobium strain was inoculated to mung bean seeds before sowing immediately. Irrigation took place two weeks intervals.

2.3 Sampling and measurement

Three vegetative samples were collected at 30, 45, and 60 days after sowing, with each sample comprising 10 randomly selected plants from each plot. Leaves and stems were separated and dried at 70° C until a constant weight was achieved. Leaf area measurements were determined as described by Radford (1967). Total dry weight per plant (g) was measured by harvesting the entire plant, drying it in an oven at a constant temperature until a stable weight was reached, and then weighing it using a precision balance; leaf area per plant (dm^2 $plant^{-1}$) was determined by scanning or manually measuring the surface area of all leaves using a leaf area meter; the leaf area index (LAI) was calculated by dividing the total leaf area (dm^2) by the corresponding ground area (dm^2) occupied by the plant; and the leaf area ratio (LAR) was obtained by dividing the total leaf area (dm^2) by the plant's total dry weight (g), providing an indicator of the plant's resource allocation towards leaf development (Equation 1).

The leaf weight ratio (LWR) was determined by measuring the dry weight of all leaves after oven-drying them to a constant weight and dividing this value by the total plant dry weight (g) (Equation 2); specific leaf area (SLA) was calculated by dividing the total leaf area (dm^2) by the corresponding leaf dry weight (g) (Equation 3),, with leaf area measured; specific leaf weight (SLW) was obtained as the ratio of leaf dry weight (g) to leaf area (dm^2) (Equation 4), indicating leaf thickness or density; relative growth rate (RGR) was computed using the natural logarithm of plant dry weight at two different time points (W1 and W2) divided by the time interval (t2 - t1) (Equation 5); crop growth rate (CGR) was derived by subtracting the initial plant dry weight (W1) from the final weight (W2) and dividing by the time interval (t2 - t1) (Equation 6), reflecting overall biomass accumulation per unit time; and net assimilation rate (NAR) was calculated using the change in dry weight (W2 - W1) multiplied by the logarithmic difference in leaf area (log A2 - log A1) (Equation 7), divided by the difference in leaf area (A2 - A1) and the time interval (t2 - t1), representing the efficiency of photosynthesis per unit leaf area over time. In equation 7, W1, A1 and W2, A2 refer to dry weight and leaf area at time t1 and t2 in weeks, respectively. .

Table 1. Soil properties of the experimental site prior to the experiment.

pH	EC ($dS\ m^{-1}$)	OM (%)	Total concentration ($mg\ kg^{-1}$)						
			N	P	K	Fe	Mn	Zn	Cu
8.2	0.38	1.09	1540	33	3132	20131	219.2	30.4	9.8

Note: EC (Electrical Conductivity); OM (Organic Matter); N (Nitrogen), P (Phosphorus), K (Potassium) – Macronutrients; Fe (Iron), Mn (Manganese), Zn (Zinc), Cu (Copper) – Micronutrients.

Leaf area ratio (LAR) = leaf area (dm^2)/plant dry weight (g) Eq (1)
Leaf weight ratio (LWR)=leaves dry weight g/plant dry weight (g) Eq (2)
Specific leaf area (SLA) =leaf area (dm^2)/leaves dry weight (g) Eq (3)
Specific leaf weight (SLW) =leaves dry weight g/leaf area (dm^2) Eq (4)
Relative growth rate (RGR) = (log W2-logW1)/t2-t1 Eq (5)
Crop growth rate (CGR) =W2-W1/t2-t1 Eq (6)
Net assimilation rate (NAR)= (W2-W1) (logA2-logA1)/(A2-A1) (t2-t1) Eq (7)

The above growth measurements were computed according to the formulae used by Watson (1958)

2.4. Yield and its components

At harvest time, the number of plants per fed was determined. Mung bean pods were harvested after 95 days from sowing. A sample of ten guarded plants was hand pulled at random from each plot for determining the following yield component: plant height (cm), No. of branches and pods $plant^{-1}$, No. of seeds pod^{-1}, seed weight $plant^{-1}$ (g) and weight of 100 seed in g.

The collected pods from three central ridges were dried and threshed and then calculated the yields fed^{-1} (seeds, straw and biological) and harvest index.

2.5 Chemical analysis

The total carbohydrate content of seeds was determined calorimetrically according to A.O.A.C, (2010).

Protein %: Nitrogen and protein contents were determined with micro Kjeldahl's apparatus according to the method described by A.O.A.C, (2010). Crude protein was determined according to Bradford (1976) (multiplying nitrogen contents by 6.25). Total carbohydrate was determined according to (A.O.A.C, 2010).

2.6. Statistical analysis

In accordance with Snedecor and Cochran's (1980), the data were statistically analyzed as a split plot. was conducted using MSTAT-C Computer Software (MSTAT-C, 1988) after testing the homogeneity of the error according to Bartlett's test, a combined analysis for both seasons were done. Means of the different treatments were compared using the least significant difference (LSD) test at $P<0.05$.

3. Results and discussion

3.1. Changes in growth characters

After 45 and 60 days from sowing, the highest dry weight of total plant biomass was recorded at the lowest plant density (75000 plant fed^{-1}) (Table 1). In contrast, the highest plant density resulted in the lowest dry weight of mung bean dry matter. This finding aligns with previous research, which highlights that biomass (dry matter) is a key determinant of yield in mung bean cultivars, accounting for over 90% of the total yield variation. Generally, increasing plant population density (plants m^{-2}) leads to greater leaf area development and, consequently, higher crop biomass accumulation. However, excessive plant density can lead to intense competition for light, nutrients, and water, ultimately reducing individual plant biomass. Thus, an optimal plant population is necessary to balance biomass accumulation and resource availability (Muchow, 1985).

The timing of photo-assimilate accumulation and remobilization varies among mung bean genotypes. Cultivated varieties tend to rely more on current photosynthesis during the reproductive stage while preserving assimilates accumulated before flowering (Bushby & Lawn, 1992). This suggests that mung bean cultivars have different strategies for carbon allocation, which may influence their response to plant density. At lower plant densities, individual plants have better access to light and resources, facilitating higher dry matter accumulation. Conversely, at higher densities, increased competition may limit the efficiency of assimilate production and remobilization, leading to lower individual plant biomass.

3.2. Physiological Attributes

Based on the combined data in Table 2 and Figure 1, the VC 1973 A variety outperformed the Kawmy-1 variety in terms of (LAR) at 30 days after sowing, SLA at 30 and 60 DAS, and NAR at 30-45 days. In contrast, Kawmy-1 exhibited higher values for these traits at the same time points. This suggests that VC 1973 A maintained a more efficient leaf structure and photosynthetic activity during early growth stages, while Kawmy-1 had a relatively higher capacity for resource utilization under the given conditions. Both mung bean varieties exhibited a progressive increase in leaf area (LA), leaf area index (LAI), and specific leaf weight (SLW) as plant age advanced up to 60 DAS. The observed trend indicates that as the plants matured, they continued expanding their photosynthetic surface area and accumulating dry matter. The data on LA and LAI reveal that both varieties achieved full canopy closure by 60 DAS, which is a crucial stage for optimizing light interception and biomass production. However, LA and leaf weight ratio (LWR) followed opposite trends as the plants aged, suggesting a shift in resource allocation from leaf expansion to dry matter accumulation. Additionally, increasing plant density led to a reduction in LA but resulted in a consistent increase in LAI up to 60 DAS.

This pattern indicates that while individual plant leaf area decreased due to competition, overall canopy development was enhanced, ensuring efficient light capture. LAI plays a crucial role in intercepting photosynthetically active radiation, whereas a larger LAI enhances light interception and boosts biomass accumulation. Plant height, an essential indicator of crop growth, is strongly influenced by environmental factors such as light availability, soil nutrients, and plant density (Rasul et al., 2012).

Table 2. Effect of mung bean variety, plant population density and their interaction on Dry matter accumulation, Specific Leaf Area and Specific Leaf Weight at 30,45 and 60 days from sowing (combined data of 2023 and 2024 seasons).

Variety	PD	Dry matter accumulation (g plant^{-1})			SLA (dm^2 g^{-1})			SLW (g dm^{-2})		
		30-DAS	45-DAS	60-DAS	30-DAS	45-DAS	60-DAS	30-DAS	45-DAS	60-DAS
VC1973 A	D1	2.88±0.37	13.68±1.11	23.8±0.91	2.01±01	1.41±0.03	1.33±0.01	0.62±0	0.89±0.02	0.91±0.01
	D2	2.6±0.40	11.43±1.13	19.32±1.15	2.08±0.06	1.5±0.02	1.43±0.01	0.59±0.01	0.83±0.01	0.86±0.001
	D3	2.44±0.42	10.46±1.24	18.31±1.61	2.13±0.1	1.56±01	1.45±0.01	0.57±0.01	0.8±0.01	0.84±0.01
	D4	2.15±0.4	8.21±0.92	12.83±0.42	2.27±0.07	1.73±0.03	1.49±0.02	0.53±01	0.72±0.02	0.81±0.005
Mean		2.77±0.44	12.04±1.21	20.42±1.12	2.12±0.06	1.55±0.02	1.42±0.01	0.58±0.01	0.81±0.01	0.86±0.01
Kawmy 1	D1	2.36±0.42	12.11±1.28	22.52±1.04	2.008±0	1.452±0.03	1.342±0.01	0.622±0	0.858±0.03	0.902±0.01
	D2	2.03±0.46	9.83±1.30	17.7±1.32	2.162±0.07	1.524±0.02	1.419±0.01	0.578±0.01	0.82±0.01	0.858±0.002
	D3	1.85±0.48	8.71±1.42	16.04±1.85	2.272±0.12	1.562±01	1.463±0.01	0.55±0.02	0.787±0.01	0.825±0.01
	D4	1.58±0.46	6.91±1.06	12.23±0.49	2.365±0.08	1.777±0.04	1.518±0.02	0.523±0.01	0.693±0.02	0.803±0.01
Mean		2.15±0.50	10.33±1.39	18.83±1.29	2.201±0.07	1.579±0.02	1.436±0.01	0.568±0.01	0.789±0.02	0.847±0.01
LSD 0.05	V	0.154	0.275	0.528	0.11	NS	0.06	NS	0.03	NS
	D	0.066	0.209	0.561	0.16	0.12	0.07	0.03	0.03	0.05
	VxD	0.055	0.286	NS	NS	NS	NS	NS	NS	NS

Note: F probability $P \le 0.05$* NS-Not Significant, SLA-Specific Leaf Area), SLW-Specific Leaf Weight, LA-Leaf Area, LAI-Leaf Area Index), LAR-Leaf Area Ratio, LWR-Leaf Weight Ratio, DAS-Days After Sowing, PD-Plant density.

Table 2. Effect of mung bean variety, plant population density, and their interaction on leaf area, leaf area index, leaf area ratio, leaf weight ratio at 30, 45, and 60 days after sowing (combined data from 2023 and 2024 seasons).

Variety	PD	LA (dm^2)			LAI			LAR (dm^2g^{-1})			LWR		
		30-DAS	45-DAS	60-DAS	30-DAS	45-DAS	60-DAS	30-DAS	45-DAS	60-DAS	30 -DAS	45-DAS	60-DAS
VC1973 A	D1	3.71±0.27	10.57±0.91	13.52±0.83	0.83±0.06	2.35±0.21	3.02±0.2	1.31±0.08	0.8±0.08	0.57±0.02	0.72±0.01	0.63±0.01	0.47±0.04
	D2	3.6±0.3	9.67±0.64	11.64±0.27	1.19±0.09	3.03±0.08	3.88±0.09	1.4±0.13	0.87±0.13	0.62±0	0.73±0.01	0.64±0.01	0.48±0.03
	D3	3.45±0.28	9.32±0.86	10.8±0.21	1.43±0.05	4.14±0.38	4.8±0.09	1.42±0.16	0.9±0.16	0.59±0.04	0.74±0.01	0.65±0.01	0.46±0
	D4	3.39±0.35	8.31±0.88	9.25±0.3	2.27±0.23	5.53±0.58	6.17±0.21	2.41±0.4	1.05±0.4	0.83±0.09	0.76±0	0.67±0	0.54±0.04
Mean		3.54±0.3	9.47±0.83	11.31±0.41	1.43±0.11	3.76±0.31	4.46±0.14	1.64±0.01	0.9±0.01	0.65±0.02	0.74±0.01	0.65±0.01	0.49±0.03
Kawmy 1	D1	3.33±0.31	9.28±1.05	12.35±0.95	0.74±0.07	2.06±0.23	2.74±0.23	1.42±0.09	0.81±0.01	0.54±0.02	0.7±0.02	0.62±0.02	0.42±0.04
	D2	3.17±0.35	8.76±0.74	11.26±0.31	1.06±0.11	2.92±0.11	3.75±0.11	1.58±0.15	0.91±0.03	0.62±0	0.72±0.01	0.63±0.01	0.44±0.03
	D3	3.06±0.32	8.1±0.99	10.51±0.24	1.36±0.06	3.6±0.11	4.67±0.11	1.64±0.18	0.96±0.05	0.64±0.04	0.73±0.01	0.64±0.01	0.46±0
	D4	2.9±0.4	7.06±1.02	8.82±0.35	1.94±0.27	4.71±0.24	5.88±0.24	1.85±0.46	1.05±0	0.7±0.11	0.76±0	0.65±0	0.48±0.05
Mean		3.11±0.35	8.3±0.95	10.73±0.47	1.27±0.13	3.32±0.16	4.26±0.16	1.62±0.02	0.93±0.02	0.62±0.02	0.73±0.01	0.63±0.01	0.45±0.03
LSD 0.05	**V**	0.17	0.35	0.52	0.11	0.15	0.23	0.02	NS	NS	0.03	0.02	0.04
	D	0.22	0.26	0.33	0.09	0.16	0.16	0.02	0.12	0.04	0.02	0.02	0.02
	VxD	NS	0.37	NS	NS	NS	NS	NS	NS	NS	0.03	0.02	NS

Note: F probability *$P \leq 0.05$** NS-Not Significant, LA-Leaf Area, LAI-Leaf Area Index, LAR-Leaf Area Ratio, LWR-Leaf Weight Ratio, DAS-Days After Sowing. PD-Plant density.

Moreover, dry biomass production is closely linked to LAI, light interception, and radiation use efficiency, making it one of the most important determinants of crop yield (Chauhan & Williams, 2018) . The interaction between planting density and variety type significantly influenced leaf area (LA) at 30 days, leaf weight ratio (LWR) at 30 and 45 days, and net assimilation rate (NAR) at 30–45 and 45–60 days after sowing, as shown in Table 3. The two varieties grown under the highest planting density exhibited the lowest LA values at 30 days after sowing, whereas VC 1973 A recorded the highest LA value. A similar trend was observed for LWR at 30 days after sowing. At 45 days after sowing, the two varieties grown at the lowest planting density exhibited the highest LWR values, while those under the highest planting density (D4) had the lowest values.

Table 3 and Figure 1 (C, D, and E) illustrate that the highest NAR values at the 30–45 and 45–60 days growth stages were recorded for the Kawmy-1 variety. However, at the highest planting density, both VC 1973 A and Kawmy-1 recorded the lowest NAR values at these same growth stages. These findings suggest that higher planting density may negatively affect NAR, potentially due to increased competition for light, nutrients, and space.

Muchow et al. (1993) reported that in a subtropical Australian environment, mung bean plants reached a leaf area index (LAI) of up to 6 by the 50th day after sowing, just after flowering, yielding 2.5 tons ha^{-1} from a planting density of 35 plants m^{-2}. In comparison, soybean crops yielding 4 tons ha^{-1} attained an LAI of 9 by day 60, while cowpea crops yielding 2.9 tons ha^{-1} reached an LAI of 6.5 by day 40. Muchow, (1985) suggested that a critical LAI of 3–4 is necessary for a crop to capture more than 90% of incident radiation during the pod-filling stage, highlighting the importance of optimizing leaf area development.

The relationship between growth parameters and yield has been explored by several researchers. Mondal et al. (2011) found that mung bean seed yield was not positively correlated with harvest index, pod size, or seed size. However, they observed that genotypes with higher LA, total dry matter (TDM), and crop growth rate (CGR) also exhibited increased seed production. Egli and Zhen-Wen (1991) proposed that seed yield per unit area is closely linked to canopy photosynthesis during flowering and pod setting, which is influenced by LAI and CGR. Mondal et al. (2012) further suggested that plants with optimal LAI and NAR have the potential to produce higher seed yields and greater biomass. If LAI reaches its peak in a shorter time frame, dry matter accumulation can be maximized. Additionally, efficient partitioning of assimilates between vegetative and reproductive structures may enhance commercial yield alongside total dry matter production.

3.3. Yield and yield components

Yield per plant and its components increased significantly with decreasing plant population densities (Table 4), while plant height decreased. The increase in yield per plant, particularly the number of pods per plant at lower plant densities, can be attributed to reduced intraspecific competition among mung bean plants.

Table 3. Effect of mung bean variety, plant population density and their interaction on Relative Growth Rate, Crop Growth Rate and Net Assimilation Rate at 30-45 and 45-60 days stages from sowing (combined data of 2023 and 2024 seasons).

Variety	PD	RGR (g g^{-1})		CGR (g dm^{-2} week^{-1})		NAR (g dm^{-2} week^{-1})	
		30-45 DAS	45-60 DAS	30-45 DAS	45-60 DAS	30-45 DAS	45-60 DAS
VC1973 A	D1	0.11±0.006	0.04±0.001	0.82±0.103	0.74±0.069	0.13±0.008	0.07±0.001
	D2	0.11±0.008	0.04±0.003	0.65±0.062	0.62±0.105	0.12±0.008	0.06±0.001
	D3	0.1±0.003	0.04±0.004	0.59±0.055	0.5±0.057	0.11±0.007	0.05±0.003
	D4	0.09±0	0.03±0.001	0.44±0.025	0.34±0.037	0.09±0.004	0.05±0.006
Mean		0.1±0.003	0.04±0.003	0.63±0.064	0.55±0.067	0.11±0.006	0.06±0.004
Kawmy 1	D1	0.101±0.007	0.041±0.001	0.675±0.118	0.642±0.08	0.119±0.009	0.068±0.002
	D2	0.098±0.01	0.036±0.003	0.563±0.071	0.471±0.121	0.108±0.01	0.058±0.002
	D3	0.096±0.003	0.035±0.004	0.512±0.063	0.42±0.065	0.1±0.008	0.054±0.003
	D4	0.09±0.001	0.031±0.001	0.404±0.029	0.288±0.042	0.084±0.005	0.041±0.007
Mean		0.096±0.003	0.036±0.003	0.54±0.073	0.455±0.077	0.102±0.007	0.055±0.004
LSD 0.05	V	NS	NS	NS	NS	0.005	NS
	D	0.003	0.005	0.04	0.05	0.005	0.004
	VxD	NS	NS	NS	NS	0.007	0.005

Note: F probability P≤0.05* NS: Not Significant, RGR-Relative Growth Rate, CGR-Crop Growth Rate and NAR-Net Assimilation Rate, DAS-Days After Sowing, PD-Plant density.

With more space available, plants could access greater resources such as light, nutrients, and water, facilitating increased photosynthesis and assimilating production (Table 4). Lower densities (D1 and D2) outperformed higher densities (225 x 10^3 and 300 x 10^3 plants fed^{-1}; D3 and D4) in terms of the number of branches per plant, number of seeds per pod, number of pods per plant, and seed weight per plant. However, plants in high-density treatments exhibited greater plant height, likely due to competition for light, leading to increased internodal elongation.

The Kawmy-1 variety produced a significantly higher number of pods and seed yield per plant compared to the VC 1973 A variety. In both cultivars, the number of pods and yield per plant declined as plant density increased, likely due to intensified competition for resources, which restricted branch formation and pod development.

Combined data in Table 4 indicate a significant interaction between variety and plant density for the number of pods and seed yield per plant. Both varieties exhibited increased pod and seed yields per plant under lower plant densities. This suggests that reduced competition allows for better nutrient uptake and assimilate partitioning, resulting in improved reproductive growth.

Data in Table 5 and Figure 2 reveal that stand count at harvest, seed yield, straw yield, and biological yield per fed of the Kawmy-1 variety were significantly higher than those of the VC 1973 A variety. The superior performance of Kawmy-1 may be attributed to its greater number of pods per plant and seeds per pod, which ultimately resulted in higher seed yield per plant (Table 4). Reduced competition from weeds under lower densities further enhanced its growth, leading to better plant establishment at harvest and improved yield components. However, both varieties exhibited comparable biological yield, harvest index, protein percentage, and total carbohydrate content, irrespective of planting density.

The highest yield per plant was observed in both varieties under the lowest plant density (75,000 plants fed^{-1}), whereas the lowest values were recorded under the highest plant density. Chauhan et al. (2018) reported similar findings, stating that the number of pods and pod weight per plant increased with decreasing plant population density, particularly with effective weed control. The number of pods per plant is a key determinant of yield, as higher pod numbers directly contribute to increased seed production. Rasul et al., (2012) also highlighted that higher yields are primarily associated with an increased number of pod-bearing branches, which enhances the number of pods and seeds per pod.

Abd El Lateef et al. (2019) observed that at the first harvest (80 days after sowing), evaluated genotypes produced over half of the total seed yield. Mung bean seeds had a protein content ranging from 21% to 23.5%, with Kawmy-1 outperforming other genotypes in protein production per hectare. Genotypic variation plays a crucial role in yield potential, as supported by studies identifying high-yielding and early-maturing genotypes such as VC1000, M53, and VC2719. Similarly, Kaur et al. (2023) reported that plant density significantly influenced dry biomass accumulation, with clear variability among mung bean varieties. For instance, the OK2000 variety exhibited 101% more pods per plant, a 42.4% higher harvest index, and a 45.3% higher yield than other varieties, though no significant yield differences were observed among the remaining varieties.

Additionally, Kaysha et al. (2020) and Gayacharan et al. (2020) emphasized the role of genetic factors in determining mung bean yield variability. These findings suggest that optimal plant density and genotype selection play crucial roles in maximizing mung bean yield. Lower plant densities reduce inter-plant competition, leading to better resource allocation and enhanced reproductive growth. The superior performance of the Kawmy-1 variety suggests its potential for higher yield production, particularly under optimal plant population management. Further research on genotype-environment interactions could help refine agronomic practices to maximize mung bean productivity under varying field conditions. The interaction between planting density and variety type significantly influenced leaf area (LA) at 30 days, leaf weight ratio (LWR) at 30 and 45 days, and net assimilation rate (NAR) at 30–45 and 45–60 days after sowing, as shown in Table 3. The two varieties grown under the highest planting density exhibited the lowest LA values at 30 days after sowing, whereas VC 1973 A recorded the highest LA value. A similar trend was observed for LWR at 30 days after sowing.

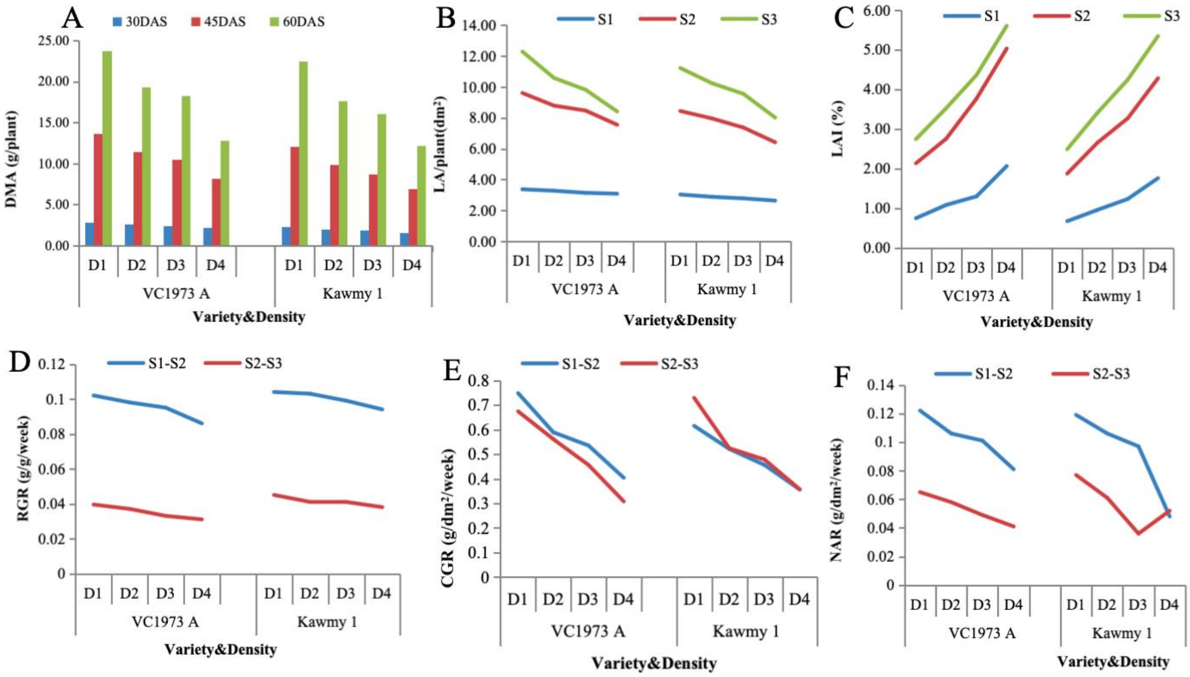

Figure 1. Effect of mung bean variety, plant population density, and their interaction on (A) dry matter accumulation, (B) leaf area (LA), (C) leaf area index (LAI), (D) relative growth rate (RGR), (E) net assimilation rate (NAR), and (F) crop growth rate (CGR) at 30, 45, and 60 days after sowing (combined data from the 2023 and 2024 seasons).

Table 4. Effect of mung bean variety, plant population density and their interaction on yield components characters (combined data of 2023 and 2024 seasons)

Variety	PD	Plant height (cm)	No. of branches (plant^{-1})	No. of pods (plant^{-1})	No. of seeds (pod^{-1})	1000 seed weight (g)	Seed yield ($\text{plant}^{-1}\ \text{g}^{-1}$)
VC1973 A	D1	74±1.55	5.5±0.06	18.4±0.06	10.8±0.06	7.1±0.06	7.2±0.2
	D2	76.3±1.15	4.8±0.06	16.9±0.06	10.6±0.1	7.1±0.1	6±0.15
	D3	77.5±1	4.4±0.1	15.1±0.06	10.5±0.15	7±0.1	5.3±0.15
	D4	79.8±0.8	3.1±0.35	12.6±0.06	10±0.06	6.9±0.1	3.9±0.06
	Mean	76.9±42.35	4.4±0.07	15.7±0.06	10.5±0.6	7±3.94	5.6±3.08
Kawmy 1	D1	70.9±1.78	5.4±0.07	17.2±0.69	10.7±0.07	7±0.07	6.8±0.23
	D2	74±1.32	4.7±0.07	15.3±0.92	10.4±0.12	6.9±0.12	5.7±0.18
	D3	75.5±1.15	4.2±0.12	13.3±1.04	10.2±0.18	6.8±0.12	5±0.18
	D4	78.2±0.92	3.8±0.4	10.6±1.15	9.9±0.07	6.7±0.12	3.8±0.07
	Mean	74.7±48.7	4.5±0.08	14.1±0.84	10.3±0.69	6.9±4.54	5.3±3.54
Density Means	D1	72.5±1.67	5.5±0.06	17.8±0.06	10.8±0.06	7.1±0.06	7±0.22
	D2	75.2±1.24	4.8±0.03	16.1±0.06	10.5±0.11	7±0.11	5.9±0.16
	D3	76.5±1.08	4.3±0.06	14.2±0.09	10.4±0.16	6.9±0.11	5.2±0.16
	D4	79±0.86	3.5±0.2	11.6±0.23	10±0.06	6.8±0.11	3.9±0.06
LSD 0.05	V	2.48	NS	0.59	0.05	0.12	0.13
	D	1.64	0.17	0.68	0.11	0.05	0.16
	VxD	NS	NS	0.96	NS	NS	0.23

Note: F probability *$P \leq 0.05$** NS: Not Significant

Table 5. Effect of mung bean variety, plant population density and their interaction on yield components characters (combined data of 2023 and 2024 seasons).

Variety	Plant density	No. of plants ($\times10^3$ fed^{-1})	Seed yield (ton fed^{-1})	Straw yield (ton fed^{-1})	Biological yield (ton fed^{-1})	Harvest index	Crude protein (%)	Total carbohydrate (%)
VC1973 A	D1	71±0.45	0.67±0.03	1.65±0.08	2.24±0.05	23.85±1.75	21.22±0.1	57.94±0.16
	D2	119.3±0.75	0.83±0.04	2.1±0.08	2.93±0.11	25.38±0.13	21.51±0.13	57.02±0.28
	D3	156.9±0.98	0.9±0.01	2.52±0.02	3.42±0.03	23.99±0.29	21.85±0.21	56.5±0.09
	D4	233.1±1.45	0.94±0.03	2.64±0.17	3.58±0.14	24.08±1.72	22.23±0.08	56.02±0.11
	Mean	147.6±0.92	0.83±0.59	2.23±0.01	3.04±0.02	24.32±0.1	21.7±0.13	56.87±0.16
Kawmy 1	D1	70.4±0.51	0.63±0.03	1.53±0.1	2.17±0.06	26.33±2.03	21.08±0.11	57.71±0.19
	D2	117.5±0.86	0.77±0.05	1.99±0.09	2.77±0.13	25.2±0.15	21.33±0.15	56.62±0.33
	D3	154.4±1.13	0.88±0.02	2.49±0.02	3.38±0.03	23.58±0.34	21.56±0.24	56.37±0.11
	D4	228.2±1.67	0.9±0.03	2.88±0.2	3.78±0.16	21.65±1.99	22.11±0.1	55.87±0.12
	Mean	142.6±1.06	0. 79±0.67	2.22±0.01	3.01±0.02	24.18±0.11	21.52±0.15	56.64±0.19
Density Means	D1	70.7±0.48	0.7±0.03	1.6±0.03	2.2±0.05	25.1±1.89	21.15±0.11	57.8±0.17
	D2	118.4±0.8	0.8±0.05	2±0.05	2.9±0.12	25.3±0.14	21.42±0.14	56.8±0.3
	D3	155.6±1.05	0.9±0.02	2.5±0.02	3.4±0.03	23.8±0.31	21.7±0.22	56.4±0.1
	D4	230.6±1.56	0.9±0.03	2.8±0.03	3.7±0.15	22.9±1.86	22.17±0.09	55.9±0.11
LSD 0.05	V	1.452	0.088	0.121	NS	0.286	0.23	0.253
D		2.563	0.121	0.143	0.011	0.154	0.18	0.198
VxD		1.848	0.132	0.121	NS	NS	NS	NS

F probability $P \leq 0.05$* NS: Not Significant

At 45 days after sowing, the two varieties grown at the lowest planting density exhibited the highest LWR values, while those under the highest planting density (D4) had the lowest values. Table 3 and Figure 1 (C, D, and E) illustrate that the highest NAR values at the 30–45 and 45–60 days growth stages were recorded for the Kawmy-1 variety. However, at the highest planting density, both VC 1973 A and Kawmy-1 recorded the lowest NAR values at these same growth stages. These findings suggest that higher planting density may negatively affect NAR, potentially due to increased competition for light, nutrients, and space.

Muchow et al. (1993) reported that in a subtropical Australian environment, mung bean plants reached a leaf area index (LAI) of up to 6 by the 50th day after sowing, just after flowering, yielding 2.5 tons ha^{-1} from a planting density of 35 plants m^{-2}. In comparison, soybean crops yielding 4 tons ha^{-1} attained a LAI of 9 by day 60, while cowpea crops yielding 2.9 tons ha^{-1} reached an LAI of 6.5 by day 40. Muchow (1985) suggested that a critical LAI of 3–4 is necessary for a crop to capture more than 90% of incident radiation during the pod-filling stage, highlighting the importance of optimizing leaf area development. The relationship between growth parameters and yield has been explored by several researchers. Mondal et al. (2011) found that mung bean seed yield was not positively correlated with harvest index, pod size, or seed size.

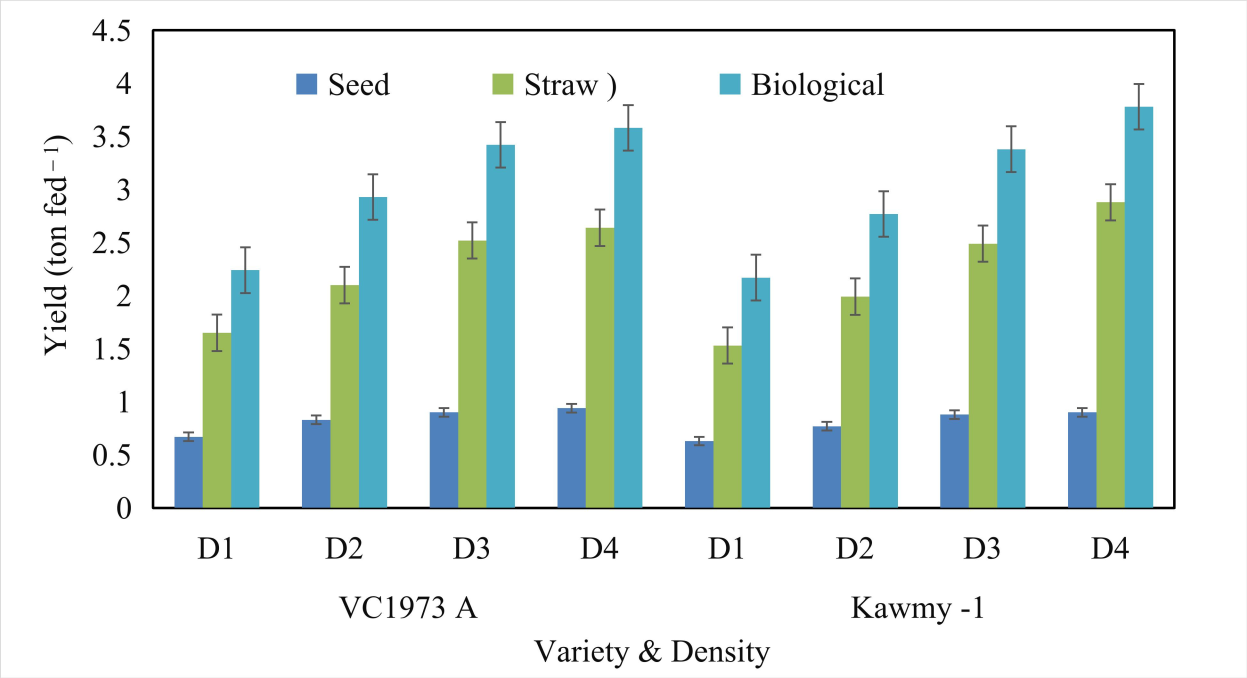

Figure 2. Effect of mung bean variety, plant population density and their interaction on seed, straw and biological yields (combined data of 2023 and 2024 seasons), Fed = Feddan = 4200 m^2

However, they observed that genotypes with higher LA, total dry matter (TDM), and crop growth rate (CGR) also exhibited increased seed production. Egli and Zhen-Wen (1991) proposed that seed yield per unit area is closely linked to canopy photosynthesis during flowering and pod setting, which is influenced by LAI and CGR. Mondal et al. (2012) further suggested that plants with optimal LAI and NAR have the potential to produce higher seed yields and greater biomass. If LAI reaches its peak in a shorter time frame, dry matter accumulation can be maximized. Additionally, efficient partitioning of assimilates between vegetative and reproductive structures may enhance commercial yield alongside total dry matter production.

3.4. Chemical analysis of the seeds

Data in Table 5 indicate significant differences in crude protein percentage among mung bean varieties. The crude protein content in mung bean genotypes was 21.70% and 21.52% for VC1973 and Kawmy-1, respectively, with the highest protein content observed under the lowest planting density (D1). Under Egyptian conditions, Farrag (1995) reported variations in protein percentage and protein yield per hectare depending on the variety.

The higher crude protein percentage in small-seeded genotypes could be attributed to the dilution effect, where crude protein is distributed within a smaller seed mass, resulting in a higher concentration. In contrast, large-seeded genotypes possess a greater mass, which reduces the crude protein percentage per unit weight. This phenomenon aligns with the findings of Kyei-Boahen et al. (2017), who reported that the grain protein concentration of cowpea followed a trend similar to grain yield but exhibited a negative correlation, meaning that higher grain yield was associated with lower protein concentration.

A similar trend was observed for total carbohydrate percentage in the two mung bean varieties. The carbohydrate content was 56.87% in VC1973 and 56.64% in Kawmy-1, with no significant difference between the genotypes. However, plant density had a significant effect, with the highest carbohydrate content recorded under the lowest planting density (D1). This could be due to reduced competition for nutrients, water, and light at lower densities, allowing for better nutrient assimilation and carbohydrate accumulation.

According to Abd El Lateef et al. (2019), mung bean seeds generally contain a protein percentage ranging from 21% to 23.5%. Their study also highlighted that Kawmy-1 exhibited superior performance in terms of both total protein yield per hectare and protein percentage. These findings reinforce the importance of genotype selection and planting density optimization for maximizing seed quality in mung bean cultivation.

4. Conclusion

This study concludes that both small-seed and large-seed varieties of mung bean can effectively tolerate biological stress resulting from higher planting densities. However, the enhanced performance of mung bean under lower densities did not fully compensate for the reduction in plant population density, which is a key determinant of yield. Therefore, while planting density plays a significant role in optimizing yield, other factors such as seed size and variety selection should also be considered for improving overall productivity.

Author Contribution

Conceptualization: Ezzat Abd El Lateef and Mostafa Abd El- Salam, Methodology: Ezzat Abd El Lateef, Mostafa Selim and Mohamed Nowar, Formal Analysis: Mohamed Nowar, Abd elazeem Salem and Mostafa Abd El-Salam, Writing-Original Draft Preparation: Ezzat Abd El Lateef, Mostafa Selim and Mohamed Nowar, Writing-Review and Editing: Ezzat Abd El Lateef, Mostafa Selim and Mohamed Nowar, Visualization: Abd elazeem Salem and Mostafa Abd El- Salam; All authors have read and agreed to the published version of the manuscript.

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