Agricultural Sciences, 2023, 14, 898-914
https://www.scirp.org/journal/as
ISSN Online: 2156-8561
ISSN Print: 2156-8553

Effects of Variety and Planting Density on Mung Bean Eco-Physiology and Yield in the Southeastern US

Jaekedah Christian[1], Dafeng Hui[1*], Navneet Kaur[1], Christina Kieffer[1], Soroush Moghaddam[1], Aisha Touray[1], Joshua Borlay[1], Matthew W. Blair[2], Srinivasa Rao Mentreddy[3], Fisseha Tegegne[2], Prabodh Illukpitiya[2]

[1]Department of Biological Sciences, Tennessee State University, Nashville, Tennessee, USA
[2]Department of Agricultural and Environmental Sciences, Tennessee State University, Nashville, Tennessee, USA
[3]Department of Biological and Environmental Sciences, Alabama Agricultural and Mechanical University, Normal, Alabama, USA
Email: *dhui@tnstate.edu

How to cite this paper: Christian, J., Hui, D.F., Kaur, N., Kieffer, C., Moghaddam, S., Touray, A., Borlay, J., Blair, M.W., Mentreddy, S.R., Tegegne, F. and Illukpitiya, P. (2023) Effects of Variety and Planting Density on Mung Bean Eco-Physiology and Yield in the Southeastern US. *Agricultural Sciences*, **14**, 898-914.
https://doi.org/10.4236/as.2023.147060

Received: March 26, 2023
Accepted: July 18, 2023
Published: July 21, 2023

Abstract

Mung bean (*Vigna radiata* L. Wilczek.) is a warm-season, C_3 pulse crop of the legume family that has been widely cultivated in Asian countries. As the demand for mung bean continues to increase in the United States, the ecophysiology, growth, and yield of mung bean varieties in the southeastern US need to be assessed. A field experiment was conducted at the Agricultural Research and Education Center of Tennessee State University to investigate the effects of four varieties (OK2000, Berken, TSU-1, AAMU-1) and three planting densities (5, 10, and 15 cm spacing) on the ecophysiology and yield of mung bean. Results showed that the relative chlorophyll content, plant height, pod dry biomass, pod number, crop yield, and harvest index significantly varied among the varieties. Density only influenced transpiration, relative chlorophyll content, and plant dry biomass. OK2000 had 101.0% more pods per plant and a 42.4% higher harvest index and produced a 45.3% higher yield than other varieties, but no significant difference in yield was found among the other three varieties. This study demonstrated that the mung bean variety OK2000 with a high yield would be ideal for commercial production in the southeastern US.

Keywords

Mung Bean, Plant Density, Ecophysiology, Growth, Yield, Legume

1. Introduction

Mung bean [*Vigna radiata* (L.) Wilczek.] is an important and short-duration pulse legume [1] that can be grown under marginal conditions with limited moisture and low soil fertility [2]. Mung bean has a distinct advantage over other long-duration summer legumes for utilization in various rotations and intercropping systems [3] [4]. With high nutritive value, its seed contains 24.2% protein, 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 [1] [5] [6] [7] [8]. Mung bean crops 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, a for-age crop, or feed for livestock [9] [10]. Mung beans originated in India and have been widely cultivated by countries in Southeast Asia, Africa, South America, Australia, and the West Indies [10]. As early as 1835, mung beans were grown in the US in states such as Oklahoma, California, and Texas where they accounted for about 90% of the US production [9]. Mung beans are also grown on a small scale in states like Kansas, Kentucky, and Tennessee. A growing awareness of its nutritional benefits has contributed to increasing demand in recent years [8], but small farmers in the US are not aware of this demand and do not grow mung beans. The demand-supply gap for mung bean has created a huge opportunity for other countries, including Australia, to increase the production of this crop to meet export demand, while deriving substantial sustainability benefits for local farming systems [8]. However, increasing the production area of mung beans to meet this demand is becoming increasingly difficult due to the preference being given to the production of high-yielding cereals by smallholder farmers, and despite the best efforts for improving mung bean varieties, the yield of this crop remains low [7].

Many studies have been conducted to understand the performance such as growth and yield and its components of mung bean. For example, Kumar *et al.* [10] investigated the physiological response, growth, and yield of four mung bean varieties under different water logging conditions and found that the photosynthesis of mung bean is about 21.21 μmol $CO_2/m^2/s$, and yield varied from 6.96 to 11.15 g dry weight/plant in the control treatment in a pot-culture experiment. Mondal *et al.* [7] suggested that the yield components depend on some physiological traits, and number of pods per plant, biomass, and yield are closely related to seed rate. To understand the physiological basis of yield difference among the genotypes of mung bean, it is essential to quantify the components of growth, and the variation, if any, that may be utilized in crop improvement [7]. Kabir and Sarkar [3] studied the effects of five varieties under three variable plant densities on the yield of mung beans with the assumption that it would help with optimum plant population per unit area and would thereby increase the yield. But thus far, not many studies have been conducted in the US, especially in the southeastern region, and the impacts of planting density on the ecophysiology and yield of mung bean varieties are still not clear.

In this study, we conducted a field experiment to test the effects of plant density on the ecophysiology, growth, and yield of four varieties of mung bean in Nashville, Tennessee. No such experiment, to the best of our knowledge, has been conducted before in this area. The specific objectives of the study were: 1) to detect whether planting density, variety, and their interaction influenced mung bean yield; 2) to determine the best variety and plant density and understand the mechanism of the yield changes due to planting density or variety. Such information concerning mung beans will be useful for the improvement of crop yield. We hypothesized that varieties and plant densities would significantly impact plant growth and yield, as different varieties have different optimal growth conditions and adapted to different environments.

2. Material and Methods

2.1. Study Site, Experimental Design, and Treatments

The experiment was carried out at the Tennessee State University (TSU) Agricultural Research and Education Center (36˚10'43.8"N 86˚49'35.4"W) in Nashville, Tennessee, during the period of May to September 2021. The soil type of the experiment site was silt loam, slightly acidic (approximate pH = 6.1), with soil nitrogen of 0.15%, phosphorus of 188.9 kg/ha, and potassium of 107.0 kg/ha (**Table 1**). Mean monthly air temperature varied from 22.5˚C to 27.3˚C and monthly precipitation varied from 56.1 to 222.0 mm during the experimental period (**Figure 1**).

Four mung bean varieties were used in this study: Oklahoma 2000 (OK2000), Oklahoma Berken (Berken), Tennessee State University-1 (TSU-1), and Alabama Agricultural and Mechanical University-1 (AAMU-1). Seeds were obtained from the Oklahoma State University, TSU, and AAMU. The length between the two rows was 45 cm. Three plant spacings of 5 cm, 10 cm, and 15 cm were used, representing 444,444, 222,222, and 148,148 plants /ha, respectively.

Table 1. Soil property at the mung bean field experimental site in Nashville, TN.

Soil property	Value
pH	6.1
Phosphorus (kg/ha)	189.9
Potassium (kg/ha)	107.0
Calcium (kg/ha)	2337.1
Magnesium (kg/ha)	248.8
Total nitrogen (%)	0.15
Carbon (%)	1.23

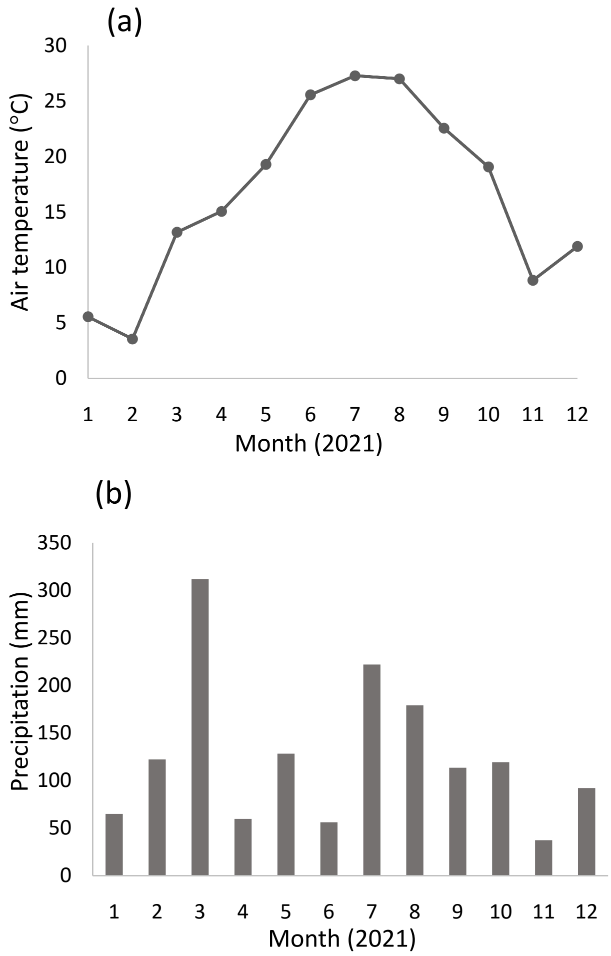

Figure 1. Monthly air temperature and precipitation in Nashville, TN in 2021. Data are from the NOAA Climate.gov.

The experiment was laid out as a split-plot design with three replications. The density was used as the main plot factor and variety as the subplot factor. In each block, varieties and densities were randomly assigned. Before planting the soil was ploughed and leveled. A pre-plant application of 40 kg N/ha urea (46-0-0) was surface applied. The total number of plots was 36. The plot size was 4 m × 2 m with 10 rows in each plot. Seeds were manually sowed on June 25, and plots were irrigated after sowing to improve seed germination. There were no major insect problems. Weeds were controlled using Roundup before the field was ploughed. During the growing season, weed control was done manually. The mung beans were harvested in late September.

2.2. Field Measurements

Leaf photosynthesis and transpiration were measured on at least three healthy, fully expanded mature leaves in each plot using the Li-6800 Portable Photosynthesis System (Li-Cor Ins., Lincoln, NE, USA) twice in August. Water use efficiency (WUE) was calculated as the ratio of leaf photosynthesis and transpiration. During measurements, CO_2 concentration was set at 400 ppm and light was set at 1500 quanta/m^2/s.

Relative chlorophyll content measurements were taken on three to five leaves in each plot, twice in August and once at the beginning of September, using the SPAD 502 Plus (Konica Minolta Optics, Japan). The height of five randomly selected plants in each plot was measured twice in August. The LAI-2200 Plant Canopy Analyzer (Li-Cor, Lincoln, NE, USA) was used for LAI measurement. We followed the manufacturer's instructions for row crop measurements. Two light readings were taken above the canopy and 6 were taken at the bottom of the canopy for each plot, in the given sequence of ABBBABBB (A for above canopy and B for below canopy). The LAI was measured in September when the maximum heights were reached.

Fifteen plants were harvested from each plot for yield on October 1. Plants representing the plot were selected sequentially in middle rows and the edge of the plot was avoided. Pods were separated from each plant. Fresh plants were weighed and dried in the oven at 70˚C to constant weight for three days. Six agronomic characteristics were recorded, including the plant dry weight, pod dry weight, the weight of seeds per plant, 100-seed weight, number of pods per plant, and number of seeds per pod. Crop yield was calculated as the weight of seeds per plant × number of plants per hectare and expressed as kg/ha. The harvest index (HI) was calculated as the seed weight divided by the plant dry weight.

2.3. Statistical Analysis

The effects of varieties, densities, and their interactions were analyzed using split-plot analysis of variance (ANOVA). Multiple comparisons were conducted using the Least Significant Difference (LSD) method when a significant effect was detected. To test whether there is a significant relationship between yield and its components, we conducted bivariate linear regression. Stepwise multiple regression was further conducted to develop the best regression model of yield with its components. Data analysis was done using SAS software (SAS 9.4, SAS Institute Inc., Cary, NC, USA).

3. Results and Discussion

3.1. Plant Physiology and Growth

Leaf photosynthesis and transpiration are two important biological processes that directly influence a plant's growth, productivity, and yield [11]. LAI plays a crucial role in capturing photosynthetically active radiation, as a larger LAI indicates more interception of solar radiation. The height of the plant is an essential aspect of crop growth and is influenced by environmental factors [12]. Dry biomass is a function of LAI and light interception, radiation use efficiency, and the most important determinant of crop yield [8]. In this study, we found no significant difference in leaf photosynthesis, transpiration, water use efficiency

(WUE), and LAI among varieties and densities, however, relative chlorophyll content and height significantly varied among the varieties and transpiration varied among the densities (**Table 2**). Density influenced transpiration and plant dry biomass. No interaction was found between variety and density for all physiological and growth variables.

As no significant difference was found in leaf photosynthesis, transpiration, and the resulting WUE among the varieties, we averaged them over the varieties and found that the mean leaf photosynthetic rate of mung bean was 28.67 μmol $CO_2/m^2/s$ and ranged from 27.88 to 29.63 μmol $CO_2/m^2/s$, the mean transpiration rate was 17.07 mmol $H_2O/m^2/s$ and ranged from 16.60 to 17.62 mmol $H_2O/m^2/s$, and the mean WUE was 1.69 μmol CO_2/mmol H_2O and ranged from 1.63 to 1.71 μmol CO_2/mmol H_2O. While transpiration and WUE were seldom reported in previous studies, photosynthesis has been widely studied. Our results were comparable to Islam [13] who reported that the photosynthesis among 8 mung bean varieties varied from 23.1 to 27.4 μmol $CO_2/m^2/s$ but higher than most other studies. For example, Nazar *et al.* [14] found that mung bean photosynthesis varies between 14 to 19 μmol $CO_2/m^2/s$ for two varieties under the control but can vary from about 8 to 28 μmol $CO_2/m^2/s$ under different salt and foliar salicylic acid treatments. Ahmed *et al.* [15] reported that the photosynthesis of mung bean is about 20 μmol $CO_2/m^2/s$ in no water stress conditions. Hossain *et al.* [16] showed that photosynthesis varied among different developmental stages and during the flowering stage, the photosynthesis of 6 mung bean varieties can reach 24.2 to 43.8 μmol $CO_2/m^2/s$.

Relative chlorophyll content was the highest in TSU-1 (44.18), but it did not differ from OK2000 (**Figure 2**). Berken had a significantly lower (41.88, 5.2%) chlorophyll content than TSU-1. Plant height was also higher for TSU-1 (63.95 cm) and AAMU-1 (62.34 cm) compared to OK2000 (57.23 cm) and Berken (56.94 cm) (**Figure 2**). These values were comparable to other previous studies. For example, Khajudparn and Tantasawat [17] reported a mean plant height of 47.6 cm (30.7 - 62.2 cm) among 56 mung bean accessions. Mondal *et al.* [18] reported that height varied from 40.1 cm to 54.5 cm among three mung bean varieties. Other studies also found that mung bean plants grew to about 50 cm (30 - 60 cm)

Table 2. Results of Split-plot Analysis of Variance (ANOVA) to detect the effects of varieties and densities on the eco-physiological variables of mung beans.

Source of Variance	df	Leaf Photosynthetic Rate (μmol $CO_2/m^2/s$)	Transpiration (mmol $H_2O/m^2/s$)	Water Use Efficiency (μmol CO_2/mmol H_2O)	Chlorophyll Content	Leaf Area Index (m^2/m^2)	Height (cm)	Dry Biomass (g/m^2)
Block	2	1.17	16.40**	0.81	1.82	2.33	0.11	0.44
Variety	3	0.64	0.97	0.83	1.90	1.14	4.31***	0.98
Density	2	1.07	9.47**	0.14	9.66**	0.64	0.07	12.86**
Variety * Density	6	0.94	1.99	1.47	1.43	1.16	1.31	1.32

*indicates significance at $p < 0.1$ level; **indicates significance at $p < 0.05$ level; ***indicates significance at $p < 0.01$ level.

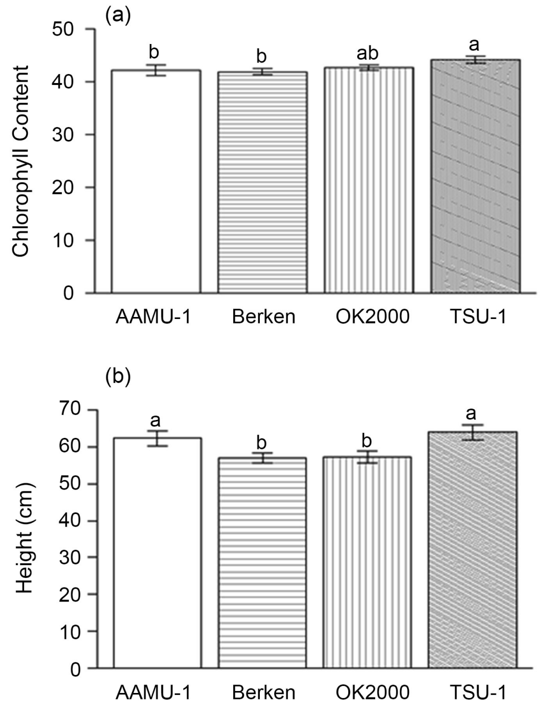

Figure 2. Mean and standard error with significant test (LSD method) of chlorophyll content and height of different mung bean varieties. Bars represent standard error of mean. Different letters denote significant differences, and the same letter denotes no significant difference.

(e.g., Kabir and Sarkar [3]; Hasan *et al.* [19]; Ahamed *et al.* [20]). In this study, we found that LAI and dry biomass were not influenced by variety. The LAI of mung bean on average was 4.86 m^2/m^2 and dry biomass was 2.70 g/plant. The LAI in this study was higher than most other reports although a large variation in LAI of mung bean has been reported in the literature. For example, Khajudparn and Tantasawat [17] evaluated 56 mung bean accessions and found LAI varied from 1.2 to 4, with a mean of 2.4. Mondal *et al.* [18] found that LAI varied between 2.8 to 5.2. Muchow *et al.* [2] reported that the maximum LAI can reach up to 6 in mung bean grown in Australia. The plant dry biomass did not differ significantly among the varieties (**Table 2**). But other studies found that dry biomass may vary among different varieties. For example, Ahamed *et al.* [19] investigated the effects of cultivars on mung bean in Bangladesh and found that total dry matter varied from 10.72 to 12.32 g/plant.

Density did not influence leaf photosynthesis, but mung beans growing in the highest density plots (5 cm spacing) consumed more water than the other two densities as leaf transpiration was higher (18.16 mmol $H_2O/m^2/s$) and significantly different in the highest density in comparison to the other two densities (**Figure 3**). There was no change in WUE among the densities. LAI and plant height were not influenced by density, but plant dry biomass differed among different densities (**Table 2**). More biomass was produced in the highest density plots than in the other density treatments (**Figure 3**). The impacts of planting density on mung beans have been widely studied and its significant impacts on plant growth have been found in most published studies. Kundu *et al.* [21] reported that plant height varied from 44.6 cm to 55.6 cm under different planting densities. Mansoor *et al.* [22] found that plant height varied from 67.53 cm to 72.21 cm among three-row spacings (20, 30, 40 cm). Ahamed *et al.* [20] found that plant density at 40 cm × 10 cm spacing produced the highest total dry matter of 11.85 g per plant. A few studies also reported no influence by density. For example, Hasan *et al.* [19] found that plant density (30 cm × 5, 10, 15 cm) did not influence plant height and yield. Overall, mung bean plants growing at high density often grow taller and produce more biomass.

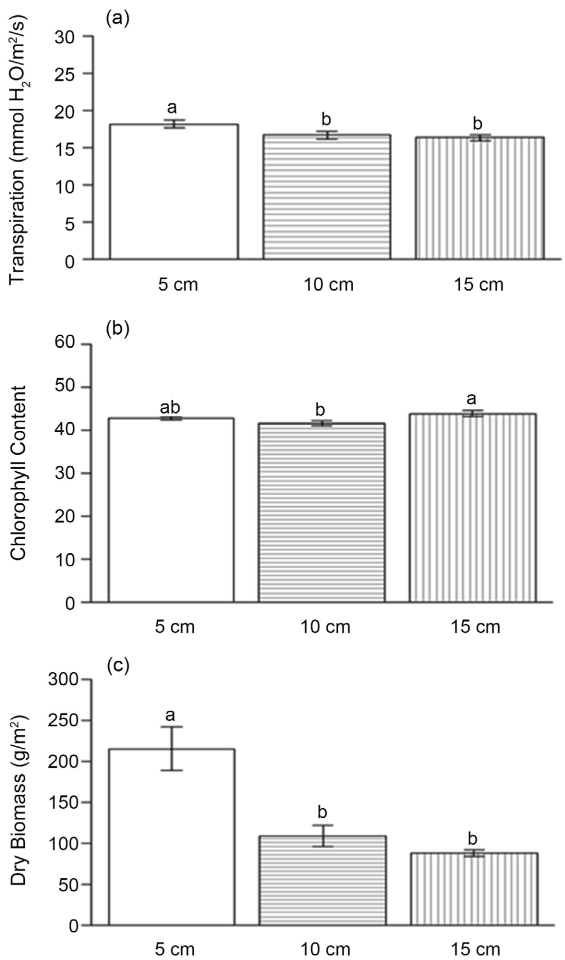

Figure 3. Mean and standard error with significant test (LSD method) of transpiration, relative chlorophyll content, and plant dry biomass of mung beans under different planting densities. Bars represent standard error of mean. Different letters denote significant differences, and the same letter denotes no significant difference.

3.2. Crop Yield and Its Components, and Harvest Index

Crop yield is a complex quantitative trait and the final product and vital goal of the farmer [17]. The yield of mung bean is determined by several yield component variables including pod number per plant, seed number per pod, 100-seed weight, and harvest index. The number of pods per plant is a key factor determining crop yield and higher yields are solely related to its multitude of pods bearing branches that produce more pods and number of seeds per pod [12]. The number of seeds per pod is another most important trait of legume crops that gives rise to the highest yields. This is the product harvested and is very important to human nutrition. 100-seed weight is one feature of mung bean varieties and may also be influenced by growing conditions. The harvest index, a measure of the production efficiency of biomass partitioning into yield, determines the capability of the plant to transport photosynthetic material to the economical part [8].

In this study, results of ANOVA showed that variety had significant impacts on pod dry biomass, number of pods per plant, number of seeds per pod, harvest index, and crop yield, but did not influence 100-seed weight (**Table 3**). There was no significant influence of planting density on all measured variables. A significant interaction was only found for pod number per plant between variety and density.

Among the three varieties, OK2000 had the highest yield (2724.8 kg/ha), significantly higher (39.6%) than AAMU-1 (1951.8 kg /ha) and (71.8%) higher than TSU-1 (1586.1 kg/ha) but was not significantly different from Berken (2086.2 kg /ha). On average, OK2000 produced a 45.3% higher yield than other varieties. OK2000 also had the highest number of pods per plant (28.70) or 637.8 g/m^2 among the four varieties which was significantly higher than any other varieties. The maximum number of seeds per pod (11.57) was also obtained from the OK2000 variety. TSU-1 had the lowest number of seeds per pod (9.81) and no significant difference in the number of seeds per pod among the other three varieties (**Figure 4**). There was also no significant difference in 100-seed weight and the mean value of the four varieties was 4.75 g (4.46 to 4.98 g). In addition, OK2000 had the highest harvest index (20.2%) but was not significantly different from TSU-1 (**Figure 4**). AAMU-1 had the lowest harvest index (13.3%). On average, OK2000 has a 42.4% higher harvest index than other varieties.

Table 3. Results of Split-plot Analysis of Variance (ANOVA) to detect the effects of varieties and densities on the yield variables of mung beans.

Source of Variance	df	Plant Pod Biomass (g/plot)	Number of Pods per Plant	Number of Seeds per Pod	100-Seed Weight (g)	Harvest Index (%)	Yield (kg/ha)
Block	2	1.13	0.93	4.62*	0.35	1.27	1.12
Variety	3	2.56*	9.23***	4.42**	1.58	9.05***	4.29**
Density	2	4.03$^{\Delta}$	0.72	1.77	0.04	0.05	2.94$^{\Delta}$
Variety * Density	6	1.19	2.35*	1.44	1.58	1.31	1.46

$^{\Delta}$ indicates $p < 0.15$ level; *indicates significance at $p < 0.05$ level; ** indicates significance at $p < 0.01$ level; *** indicates significance at $p < 0.001$ level.

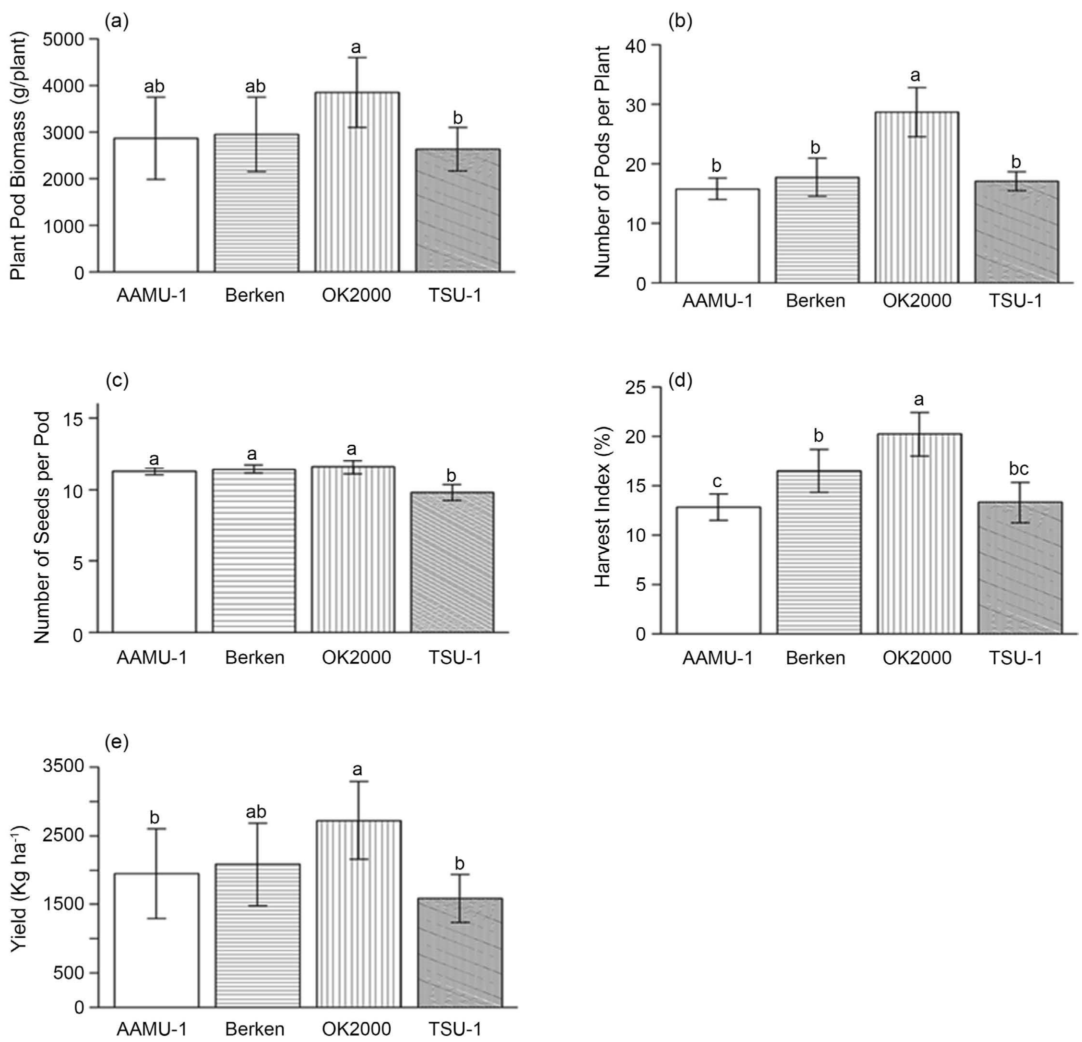

Figure 4. Mean and standard error with significant test (LSD method) of plant pod biomass, number of pods per plant, number of seeds per pod, harvest index, and crop yield of different mung bean varieties. Bars represent standard error of mean. Different letters denote significant differences, and the same letter denotes no significant difference.

Yield and its components of mung bean have been investigated in many studies and large variations in yield and its components are reported in the literature (**Table 4**). Our results were in the range of reported values in previous studies. For example, Ajio *et al.* [23] reported that the yield of mung bean varied from 919 to 3586 kg/Ha, the number of pods per plant varied from 5.7 to 17.1, and the number of seeds per pod varied from 8.0 to 12.0. Similarly, Khajudparn and Tantasawat [17] found that the mean yield of mung bean is 2038.3 kg/ha (955 - 3176 kg /ha), the number of pods per plant is 23.6 (12.2 - 49.2), the number of seeds per pod is 9.9 (6.1 - 11.6), and 100-seed weight is 5.2 (2.4 - 7.6). One study did not find a significant difference in yield (~734 kg/ ha) among varieties, only pods per plant and seeds per pod were significantly influenced [19]. While Muchow *et al.* [2] found that mung bean can produce a grain yield of 2500 kg

/ha in Australia, the lower yield of mung bean is mostly reported in previous studies. Sarkar *et al.* [24] conducted a comprehensive field experiment in Bangladesh and found that pods per plant varied from 15.14 to 17.72 among 5 varieties, seeds per pod varied from 9.68 to 10.38, 100-seed weight varied from 2.30 to 3.4 g, harvest index varied from 29.9% to 35.4%, and yield varied from 739.9 to 866.9 kg/ha. Mondal *et al.* [18] reported that among three varieties, the yield varied from 1496 to 1895 kg/ha, number of pods per plant varied from 21.3 to 33.0, number of seeds per pod varied from 8.6 to 9.3, 100-seed weight varied from 3.2 to 5.5 g, and harvest index varied from 26.4% to 34.6%. Kabir and Sarkar [3]

Table 4. Comparison of yield and its components in this study and other studies.

Study	Pods per plant	Seeds per pod	100-seed weight (g)	Harvest index (%)	Yield (kg/ha)	Plant height (cm)	Leaf area index (LAI) (m^2/m^2)	Location
This study	15.76 - 28.70	9.81 - 11.57	4.46 - 4.98	12.81 - 20.24	1586.1 - 2724.8	56.94 - 63.95	4.15 - 5.36	USA
Ahmed (2009) [29]	0 - 9	0 - 9	0 - 4.88					Pakistan
Ajio *et al.* (2016) [23]	5.69 - 17.12	8.02 - 11.95			919 - 3586	48.07 - 53.62		Uganda
Bhardwaj *et al.* (1999) [9]					805 - 3025			USA
Canci and Toker (2014) [25]	8.0 - 62.5	5.0 - 13.0	3.1 - 8.6		33.3 - 3916.6	19.5 - 91.0		Pakistan
Chattha *et al.* (2007) [30]	36.17 - 46.17	8.17 - 11.67	2.97 - 3.23	28.76 - 32.75	991 - 1480	72.50 - 76.17		Pakistan
Gayacharan *et al.* (2020) [31]		5.0 - 17.0	1.58 - 7.89			12.0 - 94.0		---
Hussain *et al.* (2011) [6]	18.13 - 32.93	6.03 - 8.37	2.87 - 4.33		430.0 - 760.0	37.80 - 55.20		Pakistan
Hussain *et al.* (2021) [32]	15.90 - 23.50	6.76 - 9.65	3.03 - 4.60	18.54 - 23.25	729 - 1271			Pakistan
Kabir and Sarkar (2008) [3]	11.56 - 14.56	9.44 - 10.53	3.02 - 3.60	26.16 - 31.38	1370 - 2580	32.10 - 45.35		Bangladesh
Miah *et al.* (2009) [33]	6.1 - 23.9	4.2 - 10.1	3.44 - 4.67	15.5 - 34.2	388.8 - 2254.0	34.3 - 63.0		Bangladesh
Kaysha *et al.* (2020) [34]	9.8 - 14.7	7.37 - 8.73	4.53 - 5.70	33.6 - 38.55	655.7 - 1244.7			Ethiopia
Khajudparn and Tantasawat (2011) [17]	12.2 - 49.2	6.1 - 11.6	2.4 - 7.6		955 - 3176	30.7 - 62.2	1.2 - 4.0	Pakistan
Kundu *et al.* (2021) [21]				20.1 - 21.3	532.7 - 592.4	44.6 - 55.6		India
Malik *et al.* (2003) [35]	15.27 - 25.63	10.06 - 12.06	2.95 - 3.56	17.01 - 24.24	705.6 - 1113.0	48.68 - 74.79		Pakistan
Mahahub *et al.* (2016) [36]	24.47 - 28.93	5.66 - 7.00	3.62 - 4.39		890 - 1320	15.62 - 64.21		Bangladesh
Mesele *et al.* (2015) [37]		6.50 - 10.30			320 - 2660	40.60 - 73.87		Ethiopia
Mondal *et al.* (2011) [38]	9.60 - 22.1	9.61 - 11.50	2.85 - 5.94	22.78 - 36.99	554 - 902		1.22 - 3.89	Bangladesh
Mondal *et al.* (2012) [7]	15.1 - 40.8	10.15 - 10.45	3.21 - 5.39	26.27 - 33.94	1496 - 1895	38.2 - 60.3	2.8 - 5.2	Bangladesh
Naeem *et al.* (2006) [39]	14.50 - 18.43	10.25 - 11.55	3.70 - 4.09		802.7 - 1122.0			Pakistan
Robu *et al.* (2014) [40]	54.23 - 73.28	11.03 - 12.62	3.85 - 4.98		1260 - 2590	39.13 - 52.30		Romania
Sarkar *et al.* (2004) [24]	15.14 - 17.72	9.68 - 10.38	2.30 - 3.40	29.9 - 35.4	739.9 - 866.9			Bangladesh
Sharma-Natu *et al.* (2004) [41]	12.82 - 32.66	7.08 - 9.19	2.30 - 2.90	27.01 - 39.54				India
Thomas *et al.* (2004) [42]				26 - 54	1230 - 3030			Australia
Uddin *et al.* (2009) [43]	21.43 - 30.77	11.00 - 12.48	3.91 - 5.07		1322 - 2057	19.90 - 60.77		Bangladesh
Yimram *et al.* (2009) [44]	5.30 - 34.40	7.68 - 14.30	2.37 - 8.11			19.90 - 80		Thailand

studied the effect of variety and planting density on the yield of mung bean and found among five varieties, the yield varied from 701.2 to 843.7 kg/ha, number of pods per plant varied from 11.6 to 12.0, number of seeds per pod varied from 9.44 to 10.53, and 100-seed weight varied from 3.02 to 3.60 g. These results and the result from this study suggested that mung bean yield and its components are influenced by many factors including mung bean varieties, environmental conditions in growing areas, and agricultural practices. The number of pods per plant could be influenced by fertilizer rate, as high nitrogen availability can facilitate the production of more branches and canopy development and contribute to high total pod production. The supply of adequate nutrients may facilitate vegetative growth and increase the number of seeds per pod [15] [23]. The 100-seed weight may vary among different varieties which might be attributed to genotypic variation in mung bean [18] [20] [23] [24]. The harvest index for mung bean was found to be around 30% [8] [25] which was slightly higher than the value in this study.

In this study, density did not influence yield and its components, but the significant tests for plant pod biomass ($F = 4.03$, $p = 0.11$) and crop yield ($F = 2.94$, $p = 0.15$) were close to significant. Both the 10 cm (868.16 g/plot or 108.52 g/m^2) and 15 cm (704.18 g/plot or 88.02 g/m^2) plant spacing was significantly different from the 5 cm plant spacing (215.3 g/m^2) (**Figure 3**). The high density tended to produce high biomass compared to the medium and low densities. The results were consistent with some previous studies that reported more biomass produced at narrow row spacing than at wider spacing [18] [21] [24]. Kundu *et al.* [21] found that close row spacing (25 cm) resulted in greater grain (583.0 kg/ha) than wider spaced crop (30 cm) and yield varied from 542.1 to 583.0 kg /ha, and harvest index varied from 21.0% to 20.2%. Rachaputi *et al.* [26] studied the effects of row spacing and plant density on yield in Australia and found that narrow row spacing resulted in 14% more yield compared to wide rows due to more intercepted radiation. Mansoor *et al.* [22] also found yield is slightly higher in the high-density treatment (1104 kg/ha). Hasan *et al.* [19] reported that plant density (30 cm × 5, 10, 15 cm) does not influence plant yield, but high density tends to produce more pods per plant and more seeds per pod. Yield components were also found to be influenced by planting density in several other studies. For example, Ajio *et al.* [23] reported that among different densities, the number of seeds per pod varied from 12.7 to 16.2, the number of seeds per pod varied from 10.6 to 11.1 and yield varied from 1171 to 2085 kg/ha. Similar findings were reported that as the plant spacing increases so does the number of pods per plant since it allows the plants to access enough nutrients, sunlight, water, and other growth requirements [19] [24] [27]. Sarkar *et al.* [24] reported that pods per plant varied from 15.21 to 17.07 among 3 plant densities, 100-seeds varied from 2.58 to 2.69 g, harvest index varied from 19.6% to 41.6%, and yield varied from 301.5 to 1183.0 kg/ha, but seeds per pot are not significant (mean is about 10 seeds per pod). Ajio *et al.* [23] studied two mung bean varieties and four plant densities (10 × 10, 20, 30, 40 cm) in Uganda and found the highest number of pods per plant was recorded at a spacing of 40 × 10 cm, and the highest grain yield at a spacing of 10 × 10 cm. The high dense (10 × 10 cm) spacing resulted in the highest mung bean grain yield in Uganda. Kabir and Sarkar [3] found that planting density influenced all variables except the number of seeds per pod. It is worth noting that these studies used different rows and plant spacings. We used 45 × 5, 10, and 15 cm spacing in this study. The row distance was longer than in most previous studies. The impacts of planting density on yield and its components need to be further explored.

3.3. Relationship between Yield and Its Components

Linear regression analysis showed that yield was significantly correlated with number of pods per plant ($Y = 497.39 + 80.295 * X_1$, $r^2 = 0.23$, $p < 0.001$, where Y is yield (kg/ha), X_1 is number of pods per plant) and 100-seed weight ($Y = -328.92 + 113.19 * X_2$, $r^2 = 0.19$, $p = 0.007$, where X_2 is 100-seed weight (g)). The yield of mung beans increased with the number of pods and 100-seed weight. The best regression model of yield and its component was: $Y = -304.92 + 6.30 * X_1 + 81.89 * X_2$, $R^2 = 0.32$, $p = 0.002$. The number of pods per plant and 100-seed weight contributed almost equally (Path coefficient was 0.37 for number of pods and 0.32 for seed weight). Yield also increased with harvest index ($Y = -5.1661 + 11.059 * X$, $r^2 = 0.40$, $p < 0.001$). Similar results have been reported in previous studies. For example, Khajudparn and Tantasawat [17] reported that seed yield is significantly and positively corrected with the number of clusters per plant, seeds per pod, dry biomass, and pods per plant of mung bean. Singh *et al.* [28] evaluated 40 genotypes of mung bean under 4 diverse environments in India and found that yield had a significant positive correlation with the number of pods per plant, number of seeds per pod, 100-seed weight, and harvest index. Other agricultural practices such as nutrient application and irrigation during drought periods that stimulate plant growth and produce high numbers of pods per plant and seeds per pod could also improve crop yield [6] [19] [29]. Summer drought in the southeastern US could reduce leaf photosynthesis and reduced mung bean yield.

4. Conclusion

This study investigated the impacts of variety and planting density on the ecophysiology, growth, and yield of mung bean in Nashville, TN, in the southeastern US. It was found that planting density only influenced the plant's dry biomass, transpiration, and chlorophyll content. Significant differences were found among the varieties of plant height, chlorophyll content, plant pod dry biomass, number of pods per plant, number of seeds per pod, harvest index, and crop yield. The interaction between variety and density only influenced the number of pods per plant. OK2000 grew slightly shorter than TSU-1 and AAMU-1, but produced the highest number of pods per plant, had the highest number of seeds per pod and harvest index, and consequently, produced the highest crop yield.

Considering that density did not significantly influence crop yield, the results of this study suggest that growing among the four mung bean varieties, OK2000 may produce the highest yield. Further field tests with variable spacing and plant population density and different planting dates are needed in order to produce a high yield of mung bean in the southeastern US. Improving the yield and production of mung bean using the modern genetic technology is also needed.

Acknowledgements

This research was supported by US Department of Agriculture (USDA) projects and the National Science Foundation (NSF) project. We thank Oklahoma Foundation Seed Stocks at Oklahoma State University for providing the OK2000 and Berken seeds, and the TSU farm technicians for the preparation of the land.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Tabasum, A., Saleem, M. and Aziz, I. (2010) Genetic Variability, Trait Association and Path Analysis of Yield and Yield Components in Mungbean (*Vigna Radiata* (L.) Wilczek). *Pakistan Journal of Botan*, **42**, 3915-3924.

[2] Muchow, R., Robertson, M. and Pengelly, B. (1993) Accumulation and Partitioning of Biomass and Nitrogen by Soybean, Mungbean and Cowpea Under Contrasting Environmental Conditions. *Field Crops Research*, **33**, 13-36. https://doi.org/10.1016/0378-4290(93)90092-2

[3] Kabir, M. and Sarkar, M. (2008) Seed Yield of Mungbean as Affected by Variety and Plant Spacing in *Kharif*-I Season. *Journal of the Bangladesh Agricultural University*, **6**, 239-244. https://doi.org/10.3329/jbau.v6i2.4817

[4] Mohammad, W., Shehzadi, S., Shah, S. and Shah, Z. (2010) Effects of Tillage and Crop Residues Management on Mungbean (*Vigna Radiata* (L.) Wilczek) Crop Yield, Nitrogen Fixation and Water Use Efficiency in Rainfed Areas. *Pakistan Journal of Botany*, **42**, 1781-1789.

[5] Miah, A., Anwar, P., Begum, M., Juraimi, A. and Islam, A. (2009) Influence of Sowing Date on Growth and Yield of Summer Mungbean Varieties. *Journal of Agriculture and Social Sciences*, **5**, 73-76.

[6] Hussain, F., Malik, A., Haji, M. and Malghani, A. (2011) Growth and Yield Response of Two Cultivars of Mungbean (*Vigna Radiata* L.) to Different Potassium Levels. *The Journal of Animal and Plant Sciences*, **21**, 622-625.

[7] Mondal, M.M.A., Puteh, A.B., Malek, M.A., Ismail, M.R., Rafii, M.Y. and Latif, M.A. (2012) Seed Yield of Mungbean (*Vigna Radiata* (L.) Wilczek) in Relation to Growth and Developmental Aspects. *The Scientific World Journal*, **2012**, Article ID: 425168. https://doi.org/10.1100/2012/425168

[8] Chauhan, Y. and Williams, R. (2018) Physiological and Agronomic Strategies to Increase Mungbean Yield in Climatically Variable Environments of Northern Australia. *Agronomy*, **8**, Article No. 83. https://doi.org/10.3390/agronomy8060083

[9] Bhardwaj, H.L., Rangappa, M. and Hamama, A.A. (1999) Chickpea, Faba Bean, Lu-

pin, Mungbean, and Pigeonpea: Potential New Crops for the Mid-Atlantic Region of the United States. In: Janick, J. Ed., *Perspectives on New Crops and New Uses*, ASHS Press, Alexandria, 202-205.

[10] Kumar, P., Pal, M., Joshi, R. and Sairam, R. (2013) Yield, Growth and Physiological Responses of Mung Bean [*Vigna radiata* (L.) Wilczek] Genotypes to Waterlogging at Vegetative Stage. *Physiology and Molecular Biology of Plants*, **19**, 209-220. https://doi.org/10.1007/s12298-012-0153-3

[11] Wilson, C., Hui, D., Nwaneri, E., Wang, J., Deng, Q., Duseja, D., *et al.* (2012) Effects of Planting Dates, Densities, and Varieties on Ecophysiology of Pigeonpea in the Southeastern United States. *Agricultural Sciences*, **3**, 147-152. https://doi.org/10.4236/as.2012.32017

[12] Rasul, F., Cheema, M., Sattar, A., Saleem, M. and Wahid, M. (2012) Evaluating the Performance of Three Mungbean Varieties Grown under Varying Inter-Row Spacing. *The Journal of Animal and Plant Sciences*, **22**, 1030-1035.

[13] Islam, M.T. (2015). Effects of High Temperature on Photosynthesis and Yield in Mungbean. *Bangladesh Journal of Botany*, **44**, 451-454. https://doi.org/10.3329/bjb.v44i3.38553

[14] Nazar, R., Iqbal, N., Syeed, S. and Khan, N. (2011) Salicylic Acid Alleviates Decreases in Photosynthesis under Salt Stress by Enhancing Nitrogen and Sulfur Assimilation and Antioxidant Metabolism Differentially in Two Mungbean Cultivars. *Journal of Plant Physiology*, **168**, 807-815. https://doi.org/10.1016/j.jplph.2010.11.001

[15] Ahmed, S., Nawata, E. and Sakuratani, T. (2006) Changes of Endogenous ABA and ACC, and their Correlations to Photosynthesis and Water Relations in Mungbean (*Vigna radiata* (L.) Wilczak cv. KPS1) during Waterlogging. *Environmental and Experimental Botany*, **57**, 278-284. https://doi.org/10.1016/j.envexpbot.2005.06.006

[16] Hossain, M., Hamid, A. and Khaliq, M. (2009) Evaluation of Mungbean (*Vigna Radiata* (L.) Wilczek) Genotypes on the Basis of Photosynthesis and Dry Matter Accumulation. *Journal of Agriculture and Rural Development*, **7**, 1-8. https://doi.org/10.3329/jard.v7i1.4415

[17] Khajudparn, P. and Tantasawat, P. (2011) Relationship and Variability of Agronomic and Physiological Characters in Mungbean. *African Journal of Biotechnology*, **10**, 9992-10000. https://doi.org/10.5897/AJB11.1288

[18] Mondal, M., Puteh, A., Malek, M. and Ismail, M. (2012) Determination of Optimum Seed Rate for Mungbean Based on Morpho-Physiological Criteria. *Legume Research*, **35**, 126-131.

[19] Hasan, R., Islam, K., Faysal, K. and Islam, M. (2018) Effects of Plant Spacing on the Yield of Mungbean Varieties. *Journal of Sylhet Agricultural University*, **5**, 141-144.

[20] Ahamed, K., Nahar, K., Hasanuzzaman, M. and Faruq, G. (2011) Growth Pattern of Mungbean at Different Planting Distance. *Academic Journal of Plant Sciences*, **4**, 6-11.

[21] Kundu, P., Ghosh, M., Kundu, C. and De, S. (2021) Response of Mungbean Varieties to Sowing Time and Spacing during Summer Season. *Journal of Food Legumes*, **34**, 228-232.

[22] Mansoor, M., Khan, H., Ayaz, M., Zubair, M. and Nadim, M. (2010) Effects of Different Planting Densities on Some Physiological Parameters of Mungbean. *Gomal University Journal of Research*, **26**, 1-8.

[23] Ajio, F., Talwana, H. and Kagoda, F. (2016) Evaluation of Mungbean Plant Spacing

for Optimising Yield in Smallholder Cropping Systems. *Regional Universities Forum for Capacity Building in Agriculture*, **14**, 403-406.

[24] Sakar, A., Kabir, H., Begum, M. and Salam, A. (2004) Yield Performance of Mungbean as Affected by Planting Date, Variety and Plant Density. *Journal of Agronomy*, **3**, 18-24. https://doi.org/10.3923/ja.2004.18.24

[25] Canci, H. and Toker, C. (2014) Yield Components in Mungbean [*Vigna radiata* (L.) Wilczek]. *Turkish Journal of Field Crops*, **19**, 258-261.

[26] Rachaputi, R., Chauhan, Y., Douglas, C., Martin, W., Krosch, S., Agius, P., *et al.* (2015) Physiological Basis of Yield Variation in Response to Row spacing and Plant Density of Mungbean Grown in Subtropical Environments. *Field Crops Research*, **183**, 14-22. https://doi.org/10.1016/j.fcr.2015.07.013

[27] Singh, T., Sharma, A. and Alie, F. (2009) Morpho-Physiological Traits as Selection Criteria for Yield Improvement in Mungbean [*Vigna radiata*. (L.) Wilczek]. *Legume Research*, **32**, 36-40.

[28] Singh, S., Singh, I., Singh, B. and Singh, O. (2008) Correlation and Path Coefficient Studies for Yield and its Components in Mungbean. *Legume Research*, **32**, 180-185.

[29] Ahmed, S. (2009) Effect of Soil Salinity on the Yield and Yield Components of Mungbean. *Pakistan Journal of Botany*, **41**, 263-268.

[30] Chattha, M., Jamil, M. and Mahmood, T. (2007) Yield and Yield Components of Mungbean as Affected by Various Weed Control Methods Under Rain-Fed Conditions of Pakistan. *International Journal of Agriculture & Biology*, **9**, 114-119.

[31] Gayacharan, Archak, S., Gupta, K., Gupta, V., Tyagi, V. and Singh, K. (2020) Mungbean Genetic Resources and Utilization. In: Nair, R., Schafleitner, R. and Lee, S.-H., Eds., *The Mungbean Genome*. *Compendium of Plant Genomes*, Springer, Cham, 9-25. https://doi.org/10.1007/978-3-030-20008-4_2

[32] Hussain, K., Ilyas, A., Wajid, A., Mehmood, N., Shakil, Q., Ilyas, A., *et al.* (2021) Impact of Integrated Nutrient Management on Production Potential of Mungbean. *Pakistan Journal of Agricultural Science*, **58**, 1123-1130. https://doi.org/10.21162/PAKJAS/21.1580

[33] Miah, A., Anwar, P., Begum, M., Juraimi, A. and Islam, A. (2009) Influence of Sowing Date on Growth and Yield of Summer Mungbean Varieties. *Journal of Agriculture and Social Sciences*, **5**, 73-76.

[34] Kaysha, K., Shanka, D. and Bibiso, M. (2020) Performance of Mung Bean (*Vigna Radiata* L.) Varieties at Different NPS Rates and Row Spacing at Kindo Koysha District, Southern Ethiopia. *Cogent Food and Agriculture*, **6**, Article 1771112. https://doi.org/10.1080/23311932.2020.1771112

[35] Malik, M., Saleem, M., Ali, A. and Mahmood, I. (2003) Effects of Nitrogen and Phosphorus Application on Growth Yield and Quality of Mungbean (*Vigna radiata* L.). *Pakistan Journal of Agricultural Science*, **40**, 133-136.

[36] Mahabub, S.T., Khan, S.H., Mazed, H.E.M.K., Sarker, S. and Tareque, H. (2016) Effect of Cow Manure on Growth, Yield and Nutrient Content of Mungbean. *Asian Research Journal of Agriculture*, **2**, 1-6. https://doi.org/10.9734/ARJA/2016/29297

[37] Mesele, A., Mehari, M. and Tesfay, M. (2015) Evaluation of Mung Bean Genotypes for Seed Yield and Other Yield Related Traits in Low Lands of South Tigray, Ethiopia. *Journal of Natural Sciences Research*, **5**, 165-167.

[38] Mondal, M.M.A., Hakim, M.A., Juraimi, A.S., Azad, M.A.K. and Karim, M.R. (2011) Contribution of Morpho-Physiological Attributes in Determining the Yield of Mungbean. *African Journal of Biotechnology*, **10**, 12897-12904.

https://doi.org/10.5897/AJB11.373

[39] Naeem, M., Iqbal, J. and Bakhsh, M. (2006) Comparative Study of Inorganic Fertilizers and Organic Manure on Yield and Yield Components of Mungbean (*Vigna radiata* L.). *Journal of Agriculture & Social Sciences*, **2**, 227-229.

[40] Robu, T., Brezeanu, C., Brezeanu, P. and Ambarus, S. (2014) Assessment of Mung Bean Yield Potential Production in the North Eastern Region of Romania. *Scientific Papers. Series A*: *Agronomy*, **57**, 310-315.

[41] Sharma-Natu, P., Pandurangam, V. and Ghildiyal, M.C. (2004) Photosynthetic Acclimation and Productivity of Mungbean Cultivars under Elevated CO_2 Concentration. *Journal of Agronomy and Crop Science*, **190**, 81-85. https://doi.org/10.1046/j.1439-037X.2003.00077.x

[42] Thomas, Robertson, M.J., Fukai, S. and Peoples, M.B. (2004) The Effect of Timing and Severity of Water Deficit on Growth, Development, Yield Accumulation and Nitrogen Fixation of Mungbean. *Field Crops Research*, **86**, 67-80. https://doi.org/10.1016/S0378-4290(03)00120-5

[43] Uddin, M.S., Amin, A.K.M.R., Ullah, M.J. and Asaduzzman, M. (2009) Interaction Effect of Variety and Different Fertilizers on the Growth and Yield of Summer Mungbean. *American-Eurasian Journal of Agronomy*, **2**, 180-184.

[44] Yimram, T., Somta, P. and Srinives, P. (2009) Genetic Variation in Cultivated Mungbean Germplasm and Its Implication in Breeding for High Yield. *Field Crops Research*, **112**, 260-266. https://doi.org/10.1016/j.fcr.2009.03.013