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Peanut Growth and Yield Responses Are Influenced by Plant Density, Microbial Consortium Inoculation, and Amino Acid Application

Alexander Calero Hurtado [1,2,*], Yanery Pérez Díaz [1], Kolima Peña Calzada [3] and Jorge Félix Meléndrez Rodríguez [3]

[1] Centro Universitario Municipal de Taguasco, University of Sancti Spiritus "José Martí Pérez", Zaza del Medio, Sancti Spiritus 62300, Cuba; yaneryemily@gmail.com
[2] Programa de Pós-Graduação em Biologia Vegetal, Departamento de Botânica e Ecologia, Instituto de Biociências, Universidade Federal de Mato Grosso, Cuiabá 78060-900, MT, Brazil
[3] Faculty of Agricultural Sciences, University of Sancti Spiritus "José Martí Pérez", Sancti Spiritus 60100, Cuba; kolimapena@gmail.com (K.P.C.); jm5865842@gmail.com (J.F.M.R.)
* Correspondence: alexcalero34@gmail.com; Tel.: +55-6599-3539-752

Abstract

Integrating optimal plant density, microbial bioinoculants, and foliar amino acid application represents a key strategy to enhance sustainable peanut production. Therefore, the objective of this research was to investigate the combined impact of plant density (P), microbial consortium (M) bioinoculants, and foliar amino acid application (A) on the morpho-physiological and agroproductive responses of peanut production. Under field conditions, the experiment was arranged in a split–split plot with four replicates. Two plant densities of 41,667 and 83,334 plants/ha were the main plots, soil inoculation with M at 0 mL m^{-2}, 100 mL m^{-2}, and 200 mL m^{-2} were the subplots, and the foliar application of VIUSID® agro at 0 mL L^{-1}, 0.60 mL L^{-1}, and 1.20 mL L^{-1} were the sub-subplots. Results indicated that peanut plant cultivated at a density of 83,334 plants/ha, inoculated with 100 mL m^{-2} of microbial consortium, and supplemented 0.60 mL L^{-1} of amino acid significantly enhanced the growth and physiological responses and increased peanut yield in a sustainable manner. Therefore, the findings of this study suggest that this integrated approach improved resource utilization, promoted balanced vegetative and reproductive development, and strengthened stress resilience, ultimately leading to higher productivity under sustainable management practices.

Keywords: amino acids; agroecology; *Arachis hypogaea*; biostimulants; foliar spraying; growth promoter; microbial consortia; yield

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1. Introduction

Global agricultural production frequently discovers environmentally friendly methods that enhance crop growth and productivity [1]. Healthy food production is achieved by considering the increase in the global population, the effects of climate change, and the gradual reliance on fertilizers derived from chemical industries, which have led to contamination and degradation of essential natural resources necessary for food production [2]. To tackle these challenges, prioritization of sustainable agricultural practices is essential, focusing on organic methods and regenerative techniques that enhance soil health and biodiversity [3]. A resilient food system that benefits both people and the planet can be established by investing in innovative technologies and supporting local farming communities [4].

Peanut is the sixth-most economical and oleaginous crop on a global scale [5]. This crop is significant due to its nutritional profile, which includes 26% protein, 48% oil, and 3% fiber, along with high levels of calcium, thiamine, and niacin, and also is considered as having the potential to serve as an economical nutritional supplement to address malnutrition [6]. Moreover, it is significant for human and animals consumption because of its vegetable oil and protein content [7]. Furthermore, Peanuts are also widely utilized as a biofertilizer, in crop rotation, and in crop associations to enhance soil chemical and physical properties and microbial diversity [8–11].

Human-managed peanut production techniques can generate problems over time owing to monoculture, seed viability loss, and decreasing yields [12]. To avoid these consequences, a variety of alternatives must be used, including proper planting density management, the application of biostimulants and biofertilizers, proper agricultural practices (crop rotation and association), and pest and disease control, among others [13]. In this context, correct plant density management is one of the most important techniques for crop production, including peanuts [14].

It is critical to use appropriate planting densities to increase peanut yield because they optimize the use of light energy by the leaves, promote nutrient absorption, increase the plant's photosynthetic rate, and increase dry matter accumulation, all of which boost production [15]. Plant density is managed using a variety of factors, including soil fertility, moisture (both soil and air), germination rate, and the agronomic properties of the varieties or cultivars [16,17]. The spatial pattern of plants is another agronomic factor that can influence crop growth and yield, as well as crop competitiveness against invasive plant species [18]. However, it has been widely reported that a uniform planting pattern improves spatial uniformity and the leaf area index, reduces reciprocal shading, and accelerates leaf closure, resulting in greater radiation capture by the leaves and increased crop growth and yield [19]. Several recent studies found that plant density altered the growth response patterns and production of peanut crops [9,14,15,17,20].

Biostimulants have also been widely utilized to increase agricultural yield and ecological management [21]. Biostimulants are microorganisms or substances (hormones, amino acids, minerals, nutrients, beneficial elements, and vitamins) that, when applied to plants, seeds, or the rhizosphere, can stimulate plant natural processes to improve nutrient absorption and efficiency, abiotic stress tolerance, and, in general, promote crop growth, development, and quality, regardless of nutrient content [22]. The use of microbial consortia as biostimulants in peanut production is a promising area of research because it can harness the synergy of various microorganisms to improve peanut plant growth and health [15]. In this way, microbial consortia can improve the efficiency of nutrient mobilization, making nutrients like phosphorus, potassium, and micronutrients more accessible to plants [23]. They can also improve biological nitrogen fixation (BNF), increase resistance to biotic and abiotic stresses, act as biological pathogen control, improve soil structure, and stimulate the production of phytohormones like auxins, gibberellins, and cytokinins, which regulate plant growth and development [24]. Several recent studies have detailed the benefits of microbial consortia in crop development and productivity, including oilseed plants like soybean [25,26], sunflower [27], and peanuts [15,28].

There are several documented findings in the literature of trials that analyze the foliar application of amino acids as promoters of plant growth [29]. Commercial VIUSID® agro is a bioproduct that possesses these qualities after undergoing a biocatalytic molecular activation process that increases its biological activity and the biochemical reactivity of all of its molecules [30]. This commercial biostimulant is made up of a combination of amino acids, including aspartic acid, arginine, glycine, and tryptophan, which function as plant growth promoters by influencing and regulating numerous physiological and biochemical processes within plant cells [31]. Several recent field experiments have shown that foliar spraying of VIUSID® agro improves growth and production in a variety of plant species, including sesame [32], chard [33], sunflower [27], and tomatoes [34].

Many recent studies have focused on determining the individual effects of plant density, inoculation with microbial consortia, and applying biostimulants. However, few studies address the combined effects of these strategies. For example, a recent study found that inoculation with a microbial consortium and foliar application of VIUSID® agro increased sunflower growth and productivity under drought conditions [27]. As a result, recent crop management advances could benefit from advantageous combinations of plant density, microbial consortium, and growth promoters to improve long-term food production. Consequently, this research aimed to explore the impact of combining plant density, microbial consortium inoculation, and foliar application of amino acid on peanut growth and productive responses.

2. Materials and Methods

2.1. Growing Conditions

The research was carried out in the field areas of the collective farm areas "Emilio R. Capestani," Cabaiguán, Sancti Spíritus, Cuba, located at 22°08′34.6″ N 79°29′04.6″ W. The Tobacco Experimental Station provided daily averages of temperature, relative humidity, and precipitation throughout the experiment.

During the experiment the Meteorological Station of Cabaiguán, Cuba, monitored daily temperatures (20–24 °C), relative humidity (75–98%), rainfall (455.60 mm), and day/night photoperiod (13/11 h). The soil in the experimental field was Sialitic Brown, with a pH = 5.9, organic matter (1.15 g kg^{-1}), organic carbon (16.88 g kg^{-1}), total nitrogen (1.68 g kg^{-1}), available phosphorous (3.33 mg kg^{-1}), and available potassium (95.39 mg kg^{-1}).

2.2. Vegetal Material

The cream-colored bush peanut variety Crema VC-504 was utilized; it is listed in the Official List of Commercial Varieties, falls under the certified category, and is untreated. Seeds were chosen based on their uniformity, color, and lack of spots. The seeds were sown manually at 0.80 m between lines and 0.15 and 0.30 m between plants, and two seeds in each space were used to achieve population densities of 83,334 and 41,667 plants/ha, respectively. Further, ten days after emerging, the plant abundance was manually eliminated, leaving one plant per space.

2.3. Experimental Design

Under field conditions, the treatments were arranged in split–split plots in a randomized block design with four replications. The main plots were two population densities (P_1 = 41,667 and P_2 = 83,334 plants/ha), while the subplots consisted of soil inoculation with a microbial consortium at 0 mL m^{-2} (M_0), 100 mL m^{-2} (M_1, 5.4×10^6 colony forming units (CFU) of *Bacillus subtilis*, 3.6×10^6 CFU of *Lactobacillus bulgaricum*, 22.3×10^6 CFU of *Saccharomyces cereviciae*), and 200 mL m^{-2} (M_2, 10.8×10^6 CFU of *Bacillus subtilis*, 7.2×10^6 CFU of *Lactobacillus bulgaricum*, 44.6×10^6 CFU of *Saccharomyces cereviciae*), and the sub-subplots were composed of the foliar application of amino acids at 0 (A_0), 0.60 mL L^{-1} (A_1), and 1.2 mL L^{-1} (A_2). The experimental plots had seven furrows, 72 m^2 for the main plot, 36 m^2 for the subplots, and 12 m^2 for the sub-subplots. The effective area for sampling and observations was 3.20 m^2.

2.4. Microbial Consortium and VIUSID® Agro Composition

The microbial consortium consists of *Bacillus subtilis* nato B/23-45-10 (5.4×10^4 colony forming units (CFU) mL^{-1}), *Lactobacillus bulgaricum* B/103-4-1 (3.6×10^4 CFU mL^{-1}), and *Saccharomyces cereviciae* L-25-7-12 (22.3×10^5 CFU mL^{-1}), with a quality certificate distributed by the Instituto Cubano de Investigaciones de Derivados de la Caña de Azúcar (ICIDCA), Cuba, with the R-ID-B-Prot-01-01 code. On the other hand, the commercial VIUSID® Agro declared composition is as follows: aspartic acid (1.6% m/m), arginine (2.5% m/m), glycine (2.4% m/m), and tryptophan (0.5% m/m), with a pH of 6.80 and a net mass of 1.14 kg [30].

2.5. Microbial Consortium and VIUSID® Agro Treatments

Following seed sowing, a pressure-retained backpack sprayer (Matabi, 16 L, Goizper Group, Antzuola, Guipuzcoa, Spain) was used to apply the microbial consortium concentrations to the soil, and both seeds and microbial consortium were promptly covered, as was recently recommended by Hurtado et al. [35]. In contrast, amino acid concentrations were sprayed on the leaves every seven days, according to the recommendation recently suggested by Calero Hurtado et al. [34], using a backpack sprayer with retained pressure (Matabi, 16 L, Goizper Group, Spain) until the phenological state R3, as was defined previously by Munger et al. [36].

2.6. Sampling Procedures and Determination of Growth and Productive Parameters

Thirty plants from each plot (120 plants per treatment) were randomly selected and marked from the usable area of each plot to measure the following growth variables at 30 and 45 days after emergence (DAE), such as plant height (PH, cm), which was measured using a graduated ruler from the base of the stem to the last internode of the main stem. Relative plant growth (RG) was determined for all plants by measuring peanut height from the shoot tip to the stem collar on the 30th and 60th days after seeding and was calculated using Equation (1).

$$\mathrm{RG} = \frac{\mathrm{PH60} - \mathrm{PH30}}{\mathrm{PH30}} \tag{1}$$

Number of stems per plant (NTP) was determined by direct counting. Total chlorophyll content (TCC, SPAD values) was measured on the first fully developed leaf (leaf + 1) from top to bottom of the plant's upper third using a portable chlorophyll meter (model TYS-B, Lab Equipment—Hinotek, Shanghai, China) between 10:00 and 11:00 a.m.

On the other hand, at harvest time (R9, 102 DAE), the following productive parameters were assessed in the same 120 plants per treatment that were evaluated for growth parameters mentioned above. The number of matured pods per plant (NMP) was determined by counting all matured fruits with seeds on the evaluated plants. We also count the matured pod with one seed (MP_1); matured pod with two seeds (MP_2); matured pod with three seeds (MP_3); and matured pod with four seeds (MP_4). The number of seeds per plant (NGP) was performed by direct count and was divided by the seed quantity by fruit. The number of seeds per plant (NSP) was determined by direct count. The number of seeds per pod (NGP) was determined by counting all seeds and dividing by all NMP. The mass of the seeds per plant (MSP, g) was determined by weighing all seeds (14%) of each head on a micro scale (model BS 124S and precision ± 0.01 g). The seed yield (SY, t ha^{-1}) of peanut plants was determined using the MSP and the number of plants/ha.

2.7. Dates Analysis

The obtained data were tested for normality and variance homogeneity using the Shapiro–Wilk and Bartlett tests, respectively. A multivariate ANOVA was used to analyze the data. When the Fisher (F) test was significant ($p < 0.05$), the Scott-Knott test ($p < 0.05$) was used for mean comparison. All statistical analyses and comparisons were performed using R software version 4.4 [37].

3. Results

3.1. Impacts of Combining Plant Density, Bacterial Consortium Inoculation, and Foliar Application of VIUSID Agro on Peanut Plant Height and Relative Growth

Plant density, microbial consortium inoculation, and amino acid application significantly affected plant height (PH) and relative growth (RG), with significant ($p < 0.01$) interaction at all factor levels (Table 1). The PH under P_2 was significantly higher than that under P_1 by 9% at PH30 and 20% at PH60 across M and A treatments. In the case of P1, M1 increased the PH30 by 20% and 23% and the PH60 by 11% and 15%, respectively, compared to the M_0 treatment (Table 1). With regard to P_2, PH30 and PH60 under M_1 were significantly higher than those under M_0 (by 26% and 13%) and M_2 (by 21% and 10%), respectively; however, the M_1 treatment exhibited a higher PH30 than the M0 treatment (Table 1). Concerning P_1 and P_2, A_2 showed higher PH30 than that under A_0 (by 14% and 38%) and under A_1 (by 10% and 34%), and the increases in PH60 were 14% and 35% higher than the A1 and A0 treatments. Additionally, A_1 resulted in significantly higher PH30 and PH60 than the A0 treatment (Table 1). In the case of the M_0, M_1, and M_2 treatments, A_2 significantly increased PH30 by 53% and 21%, by 43% and 21%, and by 62% and 19% and PH60 by 35% and 18%, by 29% and 16%, and by 57% and 24% compared to the A_0 and A_1 treatments, respectively. Nevertheless, A_1 supplementation promotes higher PH30 and PH60 than the A_0 treatment (Table 1). In the cases of PH30 and PH60, $P_2M_1A_2$ treatment was significantly higher than $P_1M_0A_0$ (by 67%) and $P_2M_0A_0$ (by 47%). In addition, compared to $P_1M_0A_0$, the rest of the combined treatments significantly increased PH30 and PH60, including the $P_2M_0A_0$ treatment (Table 1).

Table 1. Effect of different combined treatments on the plant height (PH30 and PH60) and relative growth of peanut plants (RG).

Treatments	PH30	PH60	RG
$P_1M_0A_0$	10.65 ± 0.15 j	22.35 ± 0.12 n	1.10 ± 0.01 h
$P_1M_0A_1$	12.80 ± 0.10 f	28.90 ± 0.43 j	1.26 ± 0.02 e
$P_1M_0A_2$	13.85 ± 0.35 e	32.55 ± 0.22 g	1.35 ± 0.02 c
$P_1M_1A_0$	11.60 ± 0.20 h	25.70 ± 0.37 l	1.22 ± 0.04 f
$P_1M_1A_1$	14.55 ± 0.35 d	33.55 ± 0.38 f	1.32 ± 0.01 d
$P_1M_1A_2$	16.15 ± 0.25 c	37.45 ± 0.08 d	1.31 ± 0.03 d
$P_1M_2A_0$	11.10 ± 0.20 i	24.85 ± 0.10 m	1.24 ± 0.03 e
$P_1M_2A_1$	13.75 ± 0.05 e	32.85 ± 0.09 g	1.39 ± 0.04 b
$P_1M_2A_2$	14.80 ± 0.30 d	31.55 ± 0.72 h	1.13 ± 0.01 g
$P_2M_0A_0$	12.15 ± 0.35 g	26.80 ± 0.83 k	1.21 ± 0.01 f
$P_2M_0A_1$	14.10 ± 0.40 e	32.45 ± 0.08 g	1.30 ± 0.01 d
$P_2M_0A_2$	16.20 ± 0.30 c	35.50 ± 0.13 e	1.19 ± 0.01 f
$P_2M_1A_0$	14.20 ± 0.40 e	30.55 ± 0.62 i	1.15 ± 0.02 g
$P_2M_1A_1$	16.35 ± 0.45 c	38.20 ± 0.27 c	1.34 ± 0.01 c
$P_2M_1A_2$	17.80 ± 0.10 a	42.70 ± 0.13 a	1.36 ± 0.01 c
$P_2M_2A_0$	14.65 ± 0.15 d	29.55 ± 0.78 j	1.02 ± 0.01 i
$P_2M_2A_1$	15.75 ± 0.15 c	41.10 ± 0.17 b	1.61 ± 0.01 a
$P_2M_2A_2$	17.05 ± 0.15 b	38.15 ± 0.52 c	1.24 ± 0.01 e

Table 1. *Cont.*

Treatments	PH30	PH60	RG
	F value		
P	**	**	*
M	**	**	*
A	**	**	*
P × M	**	**	**
P × A	**	**	**
M × A	*	**	**
P × M × A	*	**	**

Data are presented as mean values (n = 3) ± standard deviation (SD). Values followed by different lowercase letters in the same column indicate significant difference, according to the Scott-Knott test ($p < 0.05$); P: plant density level; M: microbial consortium concentrations; A: amino acid concentrations. * or ** indicates that the F values are significant at $p < 0.05$ or $p < 0.01$, respectively. P × M: P—M interaction; P × A: P—A interaction; M × A: M—A interaction; P × M × A: P—M—A interaction.

3.2. Impacts of Combining Plant Density, Bacterial Consortium Inoculation, and Foliar Application of VIUSID Agro on Peanut Total Chlorophyll and Number of Stems per Plant

The TCC values showed interactive effects among P, M, and A factors at TCC30 ($p < 0.01$) and TCC60 ($p < 0.01$) (Table 2). Concerning TCC30 and TCC60, P_1 was higher than that under P_2 (Table 2). In the case of both P_1 and P_2 densities, the M_1 treatment significantly increased TCC30 and TCC60 compared to the M_0 and M_2 treatments, while the M_2 treatment was significantly higher than the M_0 treatment (Table 2). Similarly, under both P_1 and P_2 densities, the A_1 and A_2 treatments significantly increased the TCC30 and TCC60 compared to the A_0 treatment. Furthermore, in the case of M_0, M_1, and M_2 treatments, applying A_2 significantly increased TCC30 and TCC60 compared to the A_0 and A_1 treatments. Whereas, at the same time, supplying A_1 showed higher TCC30 and TCC60 than the M_0 treatment ($p < 0.01$) (Table 2). On the other hand, compared to $P_1M_0A_0$ and $P_2M_0A_0$, $P_1M_0A_2$ resulted in 13% and 22% increases in peanut TCC30. Similarly, the TCC60 was highest in the $P_1M_1A_2$ treatment by 16% and 21% compared to the $P_1M_0A_0$ and $P_2M_0A_0$ treatments (Table 2).

Table 2. Effect of different combined treatments on the total chlorophyll content (SPAD values) and number of stems per plant (NTP) of peanut plants.

Treatments	TCC30	TCC60	NTP60
$P_1M_0A_0$	41.89 ± 0.97 f	41.88 ± 0.20 f	9.35 ± 0.17 e
$P_1M_0A_1$	46.36 ± 0.48 b	43.27± 0.22 e	10.19 ± 0.14 d
$P_1M_0A_2$	47.37 ± 0.52 a	44.50 ± 0.59 d	10.93 ± 0.20 c
$P_1M_1A_0$	43.54 ± 0.32 d	43.66 ± 0.40 e	11.51 ± 0.32 b
$P_1M_1A_1$	45.74 ± 0.18 b	46.83 ± 0.33 b	12.35 ± 0.52 a
$P_1M_1A_2$	47.04 ± 0.62 a	48.66 ± 0.12 a	10.39 ± 0.11 d
$P_1M_2A_0$	40.13 ± 0.23 h	42.97 ± 0.84 e	10.25 ± 0.13 d
$P_1M_2A_1$	44.68 ± 0.10 c	45.48 ± 1.42 c	9.33 ± 0.03 e
$P_1M_2A_2$	46.27 ± 0.71 b	47.68 ± 0.92 b	8.97 ± 0.06 f
$P_2M_0A_0$	38.89 ± 0.03 i	40.11 ± 0.82 g	8.71 ± 0.09 f
$P_2M_0A_1$	40.82 ± 0.27 g	43.00 ± 0.32 e	7.76 ± 0.10 h
$P_2M_0A_2$	42.11 ± 0.29 f	45.92 ± 0.13 c	7.34 ± 0.10 i
$P_2M_1A_0$	41.01 ± 0.09 g	39.02 ± 0.38 h	8.35 ± 0.06 g
$P_2M_1A_1$	43.42 ± 0.41 d	44.93 ± 0.23 d	7.78 ± 0.14 h
$P_2M_1A_2$	45.71 ± 0.86 b	42.93 ± 0.60 e	7.12 ± 0.06 i
$P_2M_2A_0$	37.28 ± 0.37 j	38.98 ± 0.31 h	8.14 ± 0.06 g
$P_2M_2A_1$	41.22 ± 0.36 g	46.23 ± 0.47 c	6.84 ± 0.01 j
$P_2M_2A_2$	42.92 ± 0.04 e	42.23 ± 0.19 f	6.47 ± 0.14 k

Table 2. *Cont.*

Treatments	TCC30	TCC60	NTP60
	F value		
P	**	**	*
M	**	**	**
A	**	**	**
P × M	**	**	**
P × A	**	**	**
M × A	**	**	**
P × M × A	**	**	**

Data are presented as mean values (n = 3) ± standard deviation (SD). Values followed by different lowercase letters in the same column indicate significance, according to the Scott-Knott test ($p < 0.05$); P: plant density level; M: microbial consortium concentrations; A: amino acid concentrations. * and ** indicates that the F values are significant at 0.05 and 0.01 probability levels, respectively. P × M: P—M interaction; P × A: P—A interaction; M × A: M—A interaction; P × M × A: P—M—A interaction.

The number of stems per plant (NTP) showed significant interactive effects among P, M, and A factors at NTP60 ($p < 0.01$) (Table 2). Regarding the M_0, M_1, and M_2 treatments, the NTP60 under P1 density was significantly higher than that under P_2 by 22% and 24%, respectively (Table 2). In the case of P_1 and P_2 densities, the A_1 and A_2 treatments decreased NTP60 by 18% and 12%, respectively, compared to the A_0 treatment. Further, under the P_2 treatment, the A_1 and A_2 treatments decreased NTP60 by 17% and 11%, respectively, when compared to the A_0 treatment (Table 2). In relation to the M_0, M_1, and M_2 treatments, applying A_1 and A_2 treatments decreased NTP30 (by 33%, 10%, and 20%) and NTP60 (by 9%, 12%, and 14%) compared to the A_0 treatment (Table 2). Additionally, the combined $P_1M_1A_1$ treatment resulted in 32% and 42% increases in NTP60 compared to the $P_1M_0A_0$ and $P_2M_0A_0$ treatments. Conversely, the TCC60 under $P_2M_2A_2$ was significantly lower than that under the other combined treatments (Table 2).

3.3. Impacts of Combining Plant Density, Bacterial Consortium Inoculation, and Foliar Application of VIUSID Agro on Peanut Productive Parameters

For MP1, MP2, MP3, MP4, and NMP, a significant ($p < 0.01$) interaction was observed among the P, M, and A factors (Table 3). In the case of MP1, P_1 density was higher than the P_2 density across all M and A concentrations (Table 3). For both P_1 and P_2 densities, MP1 increased significantly under M_0 compared to M_1 and M_2, but at the same time, M_2 was higher than the M_1 treatment (Table 3). Compared to A_0, A_1 and A_2 exhibited lower MP1, and A_1 was lower than A_2 under both P_1 and P_2 densities, respectively. Furthermore, MP1 under A_0 was significantly higher than under A_1 and A_2; however, A_1 was lower than the A_2 treatment across M_0, M_1, and M_2 concentrations (Table 3). In the case of MP1, $P_1M_0A_0$ was significantly higher than the other combined treatments (Table 3).

The MP2 production under P_2 was slightly increased compared to that under P_1 through all M and A concentrations (Table 3). For P_1, M_1 raised the MP2 by 15% and 48% compared to the M_0 and M_2 treatments, respectively ($p < 0.01$). However, M_2 lowered the MP2 by 23% compared to the M_0 treatment. It was found that M_2 and M_0 had similar effects on MP2 and were 23% higher than the M_1 treatment under P2 density (Table 3). Concerning the P_1, A_2 increased MP2 by 44% and 20% compared to the A_0 and A_1 treatments, respectively, but A_1 produced significantly more MP2 than A_0. Conversely, the MP2 had significant effects under the A_2 and A_1 treatments under P_2, but it was 10% higher than it was under the A_0 treatment (Table 3). Under M_0 and M_2, A_2 produced higher MP2 than the A_1 and A_0 treatments, but A_2 was significantly superior in relation to the A_2 treatment. In the case of M_1, A_0 showed higher MP2 production in comparison with A_1 and A_2. In contrast, under A_0, M_1 produced significantly more MP2 than M_2 and M_0. In the case of the A_1 and A_2 treatments, M_0 increased MP2 compared to the M_2 and M_1 treatments

(Table 3). On the other hand, $P_1M_0A_2$ produced more MP2 than $P_1M_0A_0$ and $P_2M_0A_0$ and also was significantly higher than the other combined treatments (Table 3).

Table 3. Effect of different combined treatments on the matured pod with different amounts of seeds and the number of matured pods per plant of peanut plants (NMP).

Treatments	MP1	MP2	MP3	MP4	NMP
$P_1M_0A_0$	7.15 ± 0.21 a	4.51 ± 0.11 k	2.36 ± 0.10 n	0.65 ± 0.06 k	13.16 ± 0.43 m
$P_1M_0A_1$	2.73 ± 0.04 g	6.84 ± 0.12 f	12.72 ± 0.16 a	4.63 ± 0.18 f	26.91 ± 0.27 c
$P_1M_0A_2$	4.77 ± 0.02 d	9.44 ± 0.14 a	6.71 ± 0.05 i	4.81 ± 0.06 f	25.73 ± 0.20 d
$P_1M_1A_0$	3.30 ± 0.06 f	8.64 ± 0.02 b	5.68 ± 0.08 j	2.82 ± 0.06 i	20.44 ± 0.42 i
$P_1M_1A_1$	2.84 ± 0.16 g	6.56 ± 0.15 f	12.42 ± 0.07 b	7.62 ± 0.08 b	29.42 ± 0.34 a
$P_1M_1A_2$	2.50 ± 0.04 h	7.65 ± 0.11 d	10.13 ± 0.12 e	9.40 ± 0.15 a	29.67 ± 0.10 a
$P_1M_2A_0$	6.09 ± 0.15 b	3.86 ± 0.12 m	2.73 ± 0.07 n	3.92 ± 0.10 h	16.60 ± 0.18 l
$P_1M_2A_1$	2.29 ± 0.01 i	5.76 ± 0.10 i	10.67 ± 0.12 d	6.41 ± 0.09 c	25.13 ± 0.13 e
$P_1M_2A_2$	3.88 ± 0.16 e	5.88 ± 0.02 i	7.49 ± 0.15 g	5.12 ± 0.02 e	22.37 ± 0.29 h
$P_2M_0A_0$	5.29 ± 0.02 c	6.18 ± 0.03 h	3.32 ± 0.08 m	2.28 ± 0.07 j	17.06 ± 0.05 l
$P_2M_0A_1$	2.44 ± 0.20 h	6.77 ± 0.09 f	10.41 ± 0.16 d	9.33 ± 0.23 a	28.94 ± 0.07 c
$P_2M_0A_2$	4.60 ± 0.17 d	7.41 ± 0.21 e	7.05 ± 0.09 h	4.67 ± 0.18 f	23.72 ± 0.10 g
$P_2M_1A_0$	3.73 ± 0.10 e	6.53 ± 0.18 f	4.15 ± 0.14 l	3.31 ± 0.08 h	17.71 ± 0.04 k
$P_2M_1A_1$	2.72 ± 0.07 g	6.55 ± 0.04 f	11.70 ± 0.21 c	7.80 ± 0.02 b	28.75 ± 0.10 b
$P_2M_1A_2$	2.32 ± 0.02 i	4.12 ± 0.11 l	12.19 ± 0.08 b	5.81 ± 0.11 d	24.44 ± 0.04 f
$P_2M_2A_0$	4.71 ± 0.07 d	5.44 ± 0.16 j	4.63 ± 0.11 k	2.68 ± 0.07 i	17.45 ± 0.16 k
$P_2M_2A_1$	2.50 ± 0.07 h	6.47 ± 0.14 f	9.31 ± 0.22 f	5.52 ± 0.10 d	23.78 ± 0.53 g
$P_2M_2A_2$	2.08 ± 0.03 j	7.99 ± 0.12 c	5.91 ± 0.13 j	3.80 ± 0.05 g	19.77 ± 0.50 j
F value					
P	**	*	**	*	**
M	**	**	**	**	**
A	**	**	**	**	**
P × M	**	**	**	**	**
P × A	**	**	**	**	**
M × A	**	**	**	**	**
P × M × A	**	**	**	**	**

Data are presented as mean values ($n = 3$) ± standard deviation (SD). Values followed by different lowercase letters in the same column indicate significance, according to Scott-Knott test ($p < 0.05$); P: plant density level; M: microbial consortium concentrations; A: amino acid concentrations. MP1: matured pod with one seed; MP2: matured pod with two seeds; MP3: matured pod with three seeds; MP4: matured pod with four seeds; * or **: indicates that the F values are significant at $p < 0.05$ or $p < 0.01$, respectively. P × M: P—M interaction; P × A: P—A interaction; M × A: M—A interaction; P × M × A: P—M—A interaction.

Under P_1, the MP3 production was significantly higher than that under P_2 in all M and A concentrations (Table 3). In the cases of P_1 and under P_2 densities, M_1 increased MP3 compared to M_0 (by 35% and 42%) and M_2 (by 30% and 35%), although M_2 showed higher MP3 than M_0. Similarly, A_1 significantly increased MP3 compared to M_0 and M_2; however, at the same time, M_2 showed a significant difference in comparison with M_2 (Table 3). Additionally, for the M_0, M_1, and M_2 concentrations, applying A_1 significantly increased MP3 compared to A_0 and A_2. However, simultaneously, A_2 exhibited higher MP3 than A_0. In contrast, under A_0, A_1, and A_2 concentrations, M_1 was significantly higher than M_0 and M_2, but at the same time, M_2 was significantly lower than M_0 (Table 3). In relation to MP3 production, the $P_1M_0A_1$ was significantly higher than the other combined treatments (Table 3).

A higher MP4 was observed under P_2 density than that under P_1 density across all M and A levels (Table 3). In the case of P_1, the MP4 production under M_1 was significantly higher than that under M_0 and M_2; nonetheless, M_2 significantly increased MP4 in relation to the M_2 treatment. Moreover, under P_2, supplying M_1 and M_2 showed similar effects on MP4 production and was significantly higher than that of the A_0 treatment (Table 3). For the P_1 density, the MP4 under A_2 was significantly higher than that under A_0 and A_1, and simultaneously, A_1 was higher than A_0. Nevertheless, in the case of P_2 density, A_1 significantly increased MP4 compared to A_0 and A_2, but at the same time, A_2 produced more MP4 than A_0 (Table 3). Additionally, under M_0, M_1, and M_2 treatments, the MP4 under A_1 was significantly higher than that under A_0 and A_2, but simultaneously, A_1

showed a significant difference relative to the A_0 treatment. Moreover, for the A_0 treatment, supplying M_1 and M_2 treatments revealed equal effects on MP4 and were higher compared to the M_0 treatment. Furthermore, under A_1 and A_2 treatments, M_1 produced more MP4 than the M_0 and M_2 treatments, while M_2 exhibited lower MP4 than the M_0 treatment (Table 3). On the other hand, the $P_1M_1A_2$ and $P_2M_0A_1$ treatments exhibited the highest MP4 production and showed a significant difference in comparison with the rest of the combined treatments (Table 3).

The NMP production was slightly higher in the P_1 than the P_2 density across M and A treatments (Table 3). For the P_1 and P_2 densities, M_1 increased NMP by 47% and 52% at M_0 and by 25% and 29% at M_2; however, the M_2 produced significantly more NMP than the M_0 treatment (Table 3). Under P_1 and P_2 densities, A_2 increased NMP by 48% and 30% and by 43% and 30%, respectively, compared to the A_0 and A_1 treatments; however, supplying A_1 treatment resulted in higher NMP than A_0 treatment (Table 3). In the cases of M_0, M_1, and M_2 treatments, the NMP under A_2 was significantly higher than that under A_0 (by 51%, 60%, and 59%) and A_1 (by 15%, 32%, and 14%), respectively; nonetheless, A_1 treatment produced significantly more NMP than A_0 treatment. Additionally, concerning the A_0, A_1, and A_2 treatments, NMP under M_1 was significantly higher than that under M_0 (by 16%, 24%, and 23%) and M_2 (by 10%, 11%, and 10%); however, M_2 treatment produced significantly more NMP than M_0 treatment (Table 3). Furthermore, the NMP was highest in the $P_1M_1A_1$ and $P_1M_1A_2$ treatments and was significantly higher than the other combined treatments (Table 3).

A significant interaction ($p < 0.01$) among P, M, and A factors was observed on NSP, NGP, MSP, and SY (Table 4). Concerning the concentrations of M and A, P_2 tended to produce significantly more NSP than the P1 density (Table 4). In comparison to the $M_0$0 and M_2 treatments, the M_1 treatment raised NSP for both P_1 and P_2 densities by 31% and 15%, respectively, whereas the M_2 treatment demonstrated greater NSP than the M_0 treatment (Table 4). In the case of both P_1 and P_2 densities, A_1 and A_2 revealed equal effects on NSP and were higher by 95% and 112% and by 96% and 114% than the A_0 treatment, respectively (Table 4). Additionally, under the M_0, M_1, and M_2 treatments, the NSP under A_2 was significantly higher than that under M_0 (by 109%, 115%, and 103%) and M_1 (by 17%, 15%, and 14%), respectively. Moreover, the A_1 was significantly more NSP than A_0 (by 80%, 87%, and 78%). Similarly, for the A_0, A_1, and A_2 treatments, the NSP under M_1 was significantly higher than that under M_0 (by 24%, 29%, and 27%) and M_2 (by 11%, 17%, and 18%), respectively. Moreover, M_2 exhibited higher NSP (by 11%, 10%, and 8%) than the M_0 treatment (Table 4). Furthermore, the $P_1M_1A_2$ and $P_2M_1A_2$ treatments revealed the highest NSP and showed a significant difference ($p < 0.01$) compared to the other combined treatments (Table 4).

In comparison to P_1 density, P_2 increased NGP under all M and A concentrations (Table 4). Concerning the P_1 and P_2 densities, the NGP under M_1 was significantly boosted under M_2 (by 11% and 12%) and M_0 (by 25% and 23%), respectively (Table 4). Additionally, under the P_1, A_2 increased NGP by 19% and 25% and by 6% and 7% over the A_0 and A_1 treatments; however, this last treatment produced significantly more NGP than the A_0 treatment (Table 4). Moreover, for the M_0, M_1, and M_2 concentrations, the NGP under A_2 was significantly higher than under A_0 (by 17%, 28%, and 26%) and under A_1 (by 5%, 7%, and 6%), respectively; nevertheless, A_1 increased NGP by 13%, 21%, and 22% when compared to the A_0 treatment (Table 4). In contrast, in the cases of A_0, A_1, and A_2 concentrations, M_1 strongly increased NGP under M_0 (by 12%, 20%, and 22%) and M_2 (by 7%, 6%, and 8%), respectively; although, at the same time, M_2 inoculation increased NGP by 6%, 13%, and 14% compared to M_0, respectively (Table 4). Furthermore, the

$P_2M_1A_2$ treatment produced the highest NGP and showed a significant difference from the other combined treatments (Table 4).

Table 4. Effect of different combined treatments on the number of seeds per plant (NSP), number of seeds per pod (NGP), mass of the seeds per plant (MSP), and seed yield (SY) of peanut plants.

Treatments	NSP	NGP	MSP	SY
$P_1M_0A_0$	23.32 ± 0.78 n	1.77 ± 0.008 m	11.67 ± 0.34 m	0.49 ± 0.020 m
$P_1M_0A_1$	73.07 ± 0.56 d	2.72 ± 0.012 e	23.86 ± 0.22 c	0.99 ± 0.015 h
$P_1M_0A_2$	63.02 ± 0.30 g	2.45 ± 0.003 i	22.81 ± 0.02 d	0.95 ± 0.006 i
$P_1M_1A_0$	48.90 ± 0.98 j	2.39 ± 0.003 j	18.12 ± 0.34 i	0.75 ± 0.10 k
$P_1M_1A_1$	83.65 ± 0.74 b	2.84 ± 0.008 c	26.08 ± 0.28 a	1.09 ± 0.016 g
$P_1M_1A_2$	85.76 ± 0.53 a	2.89 ± 0.013 b	26.31 ± 0.08 a	1.10 ± 0.001 g
$P_1M_2A_0$	37.68 ± 0.15 m	2.27 ± 0.0023 k	14.72 ± 0.14 l	0.61 ± 0.010 l
$P_1M_2A_1$	71.45 ± 0.67 e	2.84 ± 0.013 c	22.28 ± 0.11 e	0.93 ± 0.006 i
$P_1M_2A_2$	58.57 ± 0.64 h	2.62 ± 0.003 f	19.83 ± 0.23 h	0.83 ± 0.015 j
$P_2M_0A_0$	36.69 ± 0.28 m	2.15 ± 0.013 l	13.76 ± 0.04 l	1.15 ± 0.006 g
$P_2M_0A_1$	70.37 ± 0.31 e	2.88 ± 0.003 b	19.71 ± 0.04 f	1.64 ± 0.005 b
$P_2M_0A_2$	59.23 ± 0.52 h	2.50 ± 0.003 h	19.13 ± 0.09 g	1.59 ± 0.005 c
$P_2M_1A_0$	42.46 ± 0.41 k	2.40 ± 0.028 j	14.28 ± 0.03 k	1.19 ± 0.001 e
$P_2M_1A_1$	82.05 ± 0.55 c	2.85 ± 0.013 c	23.19 ± 0.08 b	1.93 ± 0.006 a
$P_2M_1A_2$	84.50 ± 0.25 a	2.92 ± 0.008 a	23.35 ± 0.06 b	1.95 ± 0.006 a
$P_2M_2A_0$	40.17 ± 0.18 l	2.30 ± 0.008 k	14.08 ± 0.13 k	1.17 ± 0.015 e
$P_2M_2A_1$	65.40 ± 1.24 e	2.75 ± 0.008 d	19.18 ± 0.41 g	1.60 ± 0.038 c
$P_2M_2A_2$	50.95 ± 2.14 i	2.58 ± 0.048 g	15.94 ± 0.40 j	1.33 ± 0.035 d
F value				
P	**	*	**	**
M	**	**	**	**
A	**	**	**	**
P × M	**	**	**	**
P × A	**	**	**	**
M × A	**	**	**	**
P × M × A	**	**	**	**

Data are presented as mean values (n = 3) ± standard deviation (SD). Values followed by different lowercase letters in the same column indicate significance, according to the Scott-Knott test ($p < 0.05$); P: plant density level; M: microbial consortium concentrations; A: amino acid concentrations. * or **: indicates that the F values are significant at $p < 0.05$ or $p < 0.01$, respectively. P × M: P—M interaction; P × A: P—A interaction; M × A: M—A interaction; P × M × A: P—M—A interaction.

In the case of the different microbial consortium and amino acid concentrations, P_1 density increased MSP in comparison with the P_2 density (Table 4). For both P_1 and P_2, the MSP under M1 was significantly increased under M0 (by 30% and 31%) and M2 (by 13% and 11%), respectively; however, M_2 resulted in a 16% increase over M_0 (Table 4). In the cases of P_1 and P_2 densities, the MSP under A_2 treatment was significantly higher than under A_0 (by 98% and 83%) and A_1 (by 59% and 50%), respectively, but at the same time, A_1 produced higher MSP than A_0 (Table 4). Therefore, under the M_0, M_1, and M_2 treatments, applying A_2 considerably raised MSP against the A_0 (by 70%, 84%, and 94%) and against A_1 (by 16%, 14%, and 13%), respectively, whereas applying A1 resulted in MSP that was 48%, 62%, and 72% higher than the A_0 treatment (Table 4). Additionally, under A_0, A_1, and A_2 treatments, the MSP under M_1 inoculation was significantly higher than that under M_0 (by 38%, 51%, and 49%) and M_2 (by 18%, 11%, and 12%), respectively, whereas M_2 showed greater MSP by 17%, 36%, and 33%, respectively, compared to the M_0 treatment (Table 4). Furthermore, the $P_1M_1A_1$ and $P_1M_1A_2$ treatments demonstrated the highest MSP and a significant difference when compared to the other combined treatments (Table 4).

Under both M and A concentrations, P_2 increased SY compared to the P_1 density (Table 4). The SY under M_1 was significantly higher than that under M_0 (31% and 81%)

and M_2 (by 13% and 7%); however, M_2 yielded 16% and 69% more than the M_0 treatment (Table 4). Similarly, at P_1 and P_2 densities, the SY was increased significantly in the A_2 treatment by 54% and 118% under A_0 and by 6% and 5% under A_1, respectively, whereas applying A_1 treatments increased the SY by 54% and 107% compared to the A_0 treatment (Table 4). Additionally, applying A_2 increased SY by 93%, 82%, and 103% and by 10%, 8%, and 7% at M_0, M_1, and M_2 concentrations, respectively, in comparison to the A_0 and A_1 treatments, while providing A_1 increased SY by 75%, 69%, and 90% in comparison to the A_0 treatment (Table 4). Under A_0, A_1, and A_2 treatments, the SY was significantly increased in the M1 treatment by 55%, 49%, and 46% under the M_0 treatment and by 28%, 14%, and 15% under M2, respectively, whereas supplying A_2 increased SY by 21%, 31%, and 37% more than the A_0 treatment (Table 4). However, in the combined $P_2M_1A_1$ and $P_2M_1A_2$ treatment, the SY was higher than that observed in response to the other combined treatments (Table 4).

4. Discussion

In contemporary agriculture, combining foliar amino acid treatments, microbial bioinoculants, and appropriate plant density is a comprehensive approach that stimulates plant physiological processes, increases resource use efficiency, and promotes sustained yield enhancement. A different way to improve plant vigor is to combine plant density with microbial bioinoculants (P_2M_1) and/or with exogenous application of amino acids (P_2A_2). This approach can improve growth rates and resilience against environmental stressors. Recent studies have shown that combining plant density with a microbial consortium improves peanut growth [15]. Similarly, combining plant density with foliar amino acid application promotes sesame and soybean growth [32,38]. The integration of these strategies creates a synergistic effect: the microbial bioinoculants enhance N fixation/uptake, P solubilization, and water status, and they secrete growth regulators (IAA, cytokinins, and GAs) or ACC-deaminase, resulting in plant height increment [39], while amino acids serves as a significant source of nitrogen and a precursor for polyamines, cand reduce the metabolic cost of synthesizing essential compounds, and allow more rapid response to high density conditions [29,34].

In agricultural studies, microbial consortia inoculation and exogenous amino acid application are widely used to promote plant growth [28,30]. This finding was consistent with recent research on cowpea [40] and sunflower plants [25]. A possible explanation for these facts is that the MC inoculation would have stimulated the phytohormone production (auxins, cytokinins, and gibberellins) and also could have enhanced nutrient availability, which are vital for cell elongation and division in stems, directly contributing to greater plant height [41]. Moreover, the foliar application can serve as precursors for proteins, enzymes, and other vital compounds, which would have allowed the plant to allocate more energy toward vegetative growth, particularly stem elongation [29]. Therefore, this result indicates that the combined effect of improved soil microbial activity and direct foliar nutrient support creates an optimal environment for vigorous peanut plants.

As discussed above, a taller peanut plant was observed under $P_2M_1A_2$ treatment. This is probably the first report that represents an important strategy of plants to improve peanut plant growth. A possible explanation for these findings can be by pairing biochemical capacity (A) with improved nutrient/water delivery and hormonal cues (M). Also, this higher pH can be explained by complementary physiological mechanisms. For example, increased plant density reduces the red: far-red light ratio, activating phytochrome-mediated shade-avoidance pathways that enhance gibberellin biosynthesis and auxin signaling, thereby promoting internode elongation [42]. However, elongation responses to density are highly influenced by the plant's nutritional and hormonal status. In this sense, the microbial consortium contributes by improving root nutrient acquisition, solubilizing phosphorus, increasing nitrogen uptake, and producing phytohormones like indole-3-acetic acid and gibberellin-like metabolites that support stem elongation [43]. In parallel, foliar-applied amino acids act as readily available nitrogen and carbon sources, accelerating protein synthesis, stimulating enzymatic activity (e.g., nitrate reductase), and interacting with hormonal pathways to maintain leaf metabolic activity during fast shoot growth [44]. Thus, plant growth stimulation is the result of an integrated mechanism in which shade-induced hormonal cues signal elongation, while microbial inoculants and amino acids provide the nutrients, metabolic precursors, and additional hormonal support required to sustain such growth without premature resource depletion.

An essential aspect of agricultural studies involves measuring total chlorophyll as SPAD values to determine the chlorophyll content in a plant's leaves [45]. In our study, at a density of 83,334 plants/ha, the resource competition is higher compared to 41,667 plants/ha. However, an optimal microbial consortium concentration can mitigate this resource competition [28]. Moreover, increased plant density in peanuts combined with an optimal MC rate likely enhances chlorophyll content through a synergistic effect, probably on nutrient uptake and plant stress mitigation [19]. For example, this microbial consortium contains plant growth-promoting microorganisms (PGPMs) like *Bacillus* spp., which helps the plant's ability to access essential nutrients like nitrogen (N) and phosphorus (P), which are critical for chlorophyll synthesis [46]. Likewise, these PGPMs have the ability to fix atmospheric N, solubilize inorganic P, and generate phytohormones that encourage root growth, thereby increasing the surface area and chlorophyll content of the plant [47]. Hence, higher plant density, when supported by microbial activity, creates a more competitive environment while still allowing for adequate resource partitioning, resulting in an increase in chlorophyll content in peanut leaves. Previous observations indicated similar effects from the combination of high plant density and soil microbial consortium inoculation in peanut plants [32]. Furthermore, the combination of high plant density and optimum microbial inoculation might boost chlorophyll content in peanut plants, promoting sustainable crop output.

Lower density (P_1) and amino acid application also significantly increased the SPAD values of peanut leaves, which was in agreement with the findings of previous research on peanut crops [15,45]. Firstly, optimal plant density ensures efficient light interception and resource utilization, reducing intraspecific competition while maximizing photosynthetic efficiency [48]. This study showed that at 83,334 plants/ha, competition for resources increases, which might have a negative influence on chlorophyll concentration due to shade and lower light availability [49]. However, the application of amino acids at 1.20 mL L^{-1} acts as a significant mitigating factor [50]. For example, at higher densities, foliar-applied amino acids at 1.20 mL L^{-1} likely can enhance N metabolism and serve as precursors for chlorophyll synthesis and improve the activity of key enzymes such as glutamine synthetase and nitrate reductase [29]. Studies have shown that exogenous amino acid application enhances photosynthetic pigment stability by improving membrane integrity and reducing chlorophyllase activity under high-density planting conditions [32,51]. Furthermore, the synergistic effect of optimal plant density and amino acid supply promotes better stomatal conductance and Rubisco activity, leading to higher chlorophyll retention [52].

As mentioned earlier, when combined, an optimized plant density, a microbial consortium inoculant, and foliar amino acids can enhance chlorophyll (SPAD) levels through complementary mechanisms related to canopy light–N status, nutrient acquisition, and chlorophyll biogenesis. For example, adjusting density customizes the canopy microclimate through mechanisms such as self-shading and leaf nitrogen dilution, enabling leaves to retain higher greenness at intermediate or optimal stand densities. This is in contrast to sparse or overcrowded conditions, where SPAD values can decrease non-linearly with increasing density [48,53]. Moreover, PGPMs can improve root functioning, which influences nutrient capture (N fixation/assimilation and P and Fe mobilization) and supply phytohormones and stress-mitigating metabolites, which together enhance leaf N status and photosynthetic apparatus—often observed as significant SPAD gains [46]. Simultaneously, exogenous amino acids then act as readily assimilable N/C units and specific biostimulants: several serve as precursors or regulators for chlorophyll synthesis and PSII electron transfer, while also bolstering antioxidant systems; these effects translate into measurable increases in chlorophyll/SPAD across crops [54]. Recent crop studies also confirm that targeted foliar amino acids elevate chlorophyll pools and photosynthetic performance, reinforcing their role as a fast, foliar route to sustain pigment content alongside microbial and density management [27,55]. These results suggest that plant density, microbial consortium inoculant, and foliar amino acids may be used as useful alternatives in modern agriculture because they play an important role in ensuring sustainable peanut growth and fostering beneficial plant and soil properties.

A key agronomic characteristic of peanut plants is the quantity of stems produced, which has a direct impact on photosynthetic capacity, canopy architecture, and pod yield [15]. For example, at lower P_1 density, peanut plants experience reduced competition, which allows greater interception of light and allocation of resources to branching and stem development, often resulting in a higher number of stems per plant [15,28]. Conversely, at P_2, the increased proximity of plants intensifies shading and root competition, which tends to reduce branching and individual stem production but increases stem number per unit area due to the higher plant population [39]. Inoculating peanut plants with microbial consortia (100 mL m^{-2}) can boost stem production at both P_1 and P_2 densities by improving nutrient acquisition, hormonal regulation, and stress mitigation [56,57]. Likewise, foliar applications of amino acid (A_1) can increase NTP in both plant densities by acting as signaling molecules, precursors for protein synthesis, or energy-sparing additives [27,34]. Thus, in our study, the higher NTP observed at the $P_1M_1A_1$ treatment is probably because, together, these practices can create a more favorable physiological environment that maximizes vegetative vigor, allowing peanut plants to increase stem number under both lower and optimal densities by reducing resource limitations and stimulating endogenous growth-regulating mechanisms.

Plant density had a significant impact on matured pod production. In this study the P_1 density promotes higher MP1 and MP2 but significantly produces less MP3, MP4, and NMP compared to the P_2 density. These facts can be interpreted as a density-dependent tradeoff, whereby optimal density supports a higher number of seeds per pod through effective resource partitioning, while lower density promotes pod initiation but compromises pod filling [58]. Moreover, under both P_1 and P_2 densities, the inoculation with M_1 or foliar application of A_2 produced more MP3, MP4, and NMP. These positive effects can be attributed to synergistic effects on peanut reproductive development and resource allocation [59]. Furthermore, $P_2M_1A_2$ and $P_2M_1A_1$ treatments yielded the highest NMP values, highlighting how reduced competition allows for more efficient resource allocation toward reproductive development [60]. These combined alternatives can increase carbon and nitrogen partitioning to reproductive sinks, lowering the incidence of poorly filled pods with one or two seeds and favoring the formation of pods with more seeds [59,61]. These findings suggest that combining plant density, microbial inoculation, and amino acid supplementation maximizes resource utilization, resulting in improved peanut seed quality and quantity.

In this study, P_2 density improves the NSP, NGP, NMP, and SY in comparison with the P_2 density. These results can be explained by the fact that an optimal planting density can improve peanut productivity traits such as NGP, NSP, MSP, and SY by balancing intraspecific competition and efficient resource use [61,62]. For example, an optimal density maximizes light interception and improves canopy structure, favoring better assimilate partitioning towards reproductive organs, increasing pod and seed number per plant [60]. Conversely, at lower densities, even while individual plants have better access to light, nutrients, and water, the total canopy fails to intercept solar radiation effectively, resulting in poorer photosynthetic efficiency at the field scale [14].

On the other hand, soil inoculation with M_1 combined with foliar application of A_1 or A_2 can synergistically enhance peanut yield components and productivity under both P_1 and P_2 density because these practices can improve plant nutrient acquisition, stress tolerance, and metabolic efficiency [15,63]. This synergy effect between M_1 and A_1/A_2 also aligns with recent findings observed in sunflower plants under water-deficit conditions [27]. Our results demonstrated a synergy effect facilitated by both vegetative vigor (boosting PH and NTP) and reproductive efficiency (improving NMP, NSP, NGP, MSP, and SY), especially at P_2. This dual approach decreases density-induced stress at P_2 populations while compensating for decreased interplant competition at P_1, resulting in stable and increased peanut yield. Additionally, a notable improvement of NMP, NSP, NGP, MSP, and SY was observed in the $P_2M_1A_1$ and $P_2M_1A_2$ treatments. The simultaneous optimization of planting density, soil inoculation with microbial consortia, and foliar application of amino acids can significantly enhance the yield components and overall productivity of peanut plants due to their synergistic effects on resource use efficiency, physiological performance, and soil–plant interactions [15,64]. Moreover, when applied together, these strategies create a favorable agroecosystem where nutrient availability, metabolic efficiency, and canopy structure are harmonized, ultimately resulting in improved pod filling, higher seed weight, and increased peanut yield potential [15,28,32]. Furthermore, this integrated strategy aligns with broader trends in sustainable peanut production that emphasize reducing reliance on chemical fertilizers, improving microbial health, and maximizing yield through sustainable agronomy strategies.

5. Conclusions

In summary, the synergistic use of microbial consortium inoculants and foliar-applied amino acids, particularly under high plant density (83,334 plants/ha), substantially boosted peanut growth and yield components—PH, NSP, NGP, MSP, and overall seed yield. The findings of this study showed that combining $P_2M_1A_1$ or $P_2M_1A_2$ significantly enhanced peanut growth and yield, resulting in a viable strategy for promoting sustainable peanut production. Collectively, the findings of this highlight that the combined manipulation of plant density, microbial inoculation, and amino acid foliar application offers a powerful agronomic strategy to optimize peanut reproductive efficiency and yield, which could be offered as programs for the sustainable development of modern agriculture.

As far as policy is concerned, these findings underscore the significance of encouraging sustainable intensification methods that lessen dependency on artificial inputs and enhance resource efficiency. Promoting the use of biostimulants and bioinoculants through extension initiatives, subsidies, and agricultural policies could hasten the shift to environmentally friendly and climate-smart production methods. In order to assess these practices' long-term impacts on crop resilience and soil health, future research should concentrate on scaling them under various agroecological conditions and incorporating them into comprehensive management frameworks. In order to improve farmer profitability, guarantee food security, and support global sustainability objectives in agriculture, such initiatives will be essential.

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Abbreviations

The following abbreviations are used in this manuscript:

P	Plant density
M	Microbial consortium
A	Amino acid
DAS	Days after seeding
PH	Plant height
RG	Relative growth
TCC	Total chlorophyll content
NTP	Number of stems per plant
NMP	Number of matured pods per plant
MP1	Matured pod with one seed
MP2	Matured pod with two seeds
MP3	Matured pod with three seeds
MP4	Matured pod with four seeds
NSP	Number of seeds per plant
NGP	Number of seeds per pod
MSP	Mass of the seeds per plant
SY	Seed yield

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