

The integrated application of compost sources, chemical fertilizers, and foliar fertilizers as a strategy for plant nutrient management for bush beans in high-Andean zones

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Abstract

Integrated plant nutrient management (IPNM) strategies improve the income of growers. Therefore, the objective of this study was to evaluate the growth and yield of bush beans (*Phaseolus vulgaris* L.) of the 'Bacatá' cultivar under different nutrition management strategies using different chemical fertilizer sources (edaphic and foliar) and compost in three high-Andean environments in Colombia. The IPNM treatments were set up in high- and low-rainfall zones (Gachalá vs. Guachetá) and in a greenhouse. The IPNM comprised plants without nutrients (AC); full dose NPK (EC); a mixture of compost based on wastes (20%), NPK (80%), and foliar fertilizer (GCFF); a mixture of compost based on waste (20%) and NPK (80%)(GC); a mixture of commercial compost (20%), NPK (80%), and foliar fertilizer (CCFF); and a mixture of commercial compost (20%) and NPK (80%) (CC). The results showed that the zones with higher rainfall (Gachalá) generally had a higher relative and absolute growth rate than the low rainfall zone (Gachetá) and greenhouse at different sample points. The IPNM treatments with a mixture of compost compounds showed agronomic efficiency similar to that of plants treated with chemical fertilizers only. Plants without any nutrient application showed the lowest yield parameters, reaching a production close to 1100 kg ha⁻¹, compared to the other nutrient application treatments that reached a production close to 1600 kg ha⁻¹. These results indicate that IPNM treatment is an important tool for improving the productivity of common bush beans grown in Andean agroecosystems.

Keywords: agronomic efficiency; biomass accumulation; bush bean; chemical nutrition; organic fertilizers; yield parameters

Introduction

Common bean (*Phaseolus vulgaris* L.) is the most cultivated and consumed grain legume in the world and plays an important role in the human diet because of its high protein and mineral content (Torres and

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Farah, 2017). Worldwide production of 55,627,164 t in 38,038,865 ha was registered for green and dry beans in 2017 and 27,545,942 t of dry beans in 2020 (FAOSTAT, 2022). Studies have projected a reduction in climatic suitability due to heat and drought stress in most bean crops in South America (Heinemann *et al.*, 2017). When beans are sown in various environments in small areas, specific crop management problems can arise, which can affect many farmers. Most of these problems occur in peasant production systems with few efficient marketing channels, high investment levels, and risks caused by adverse environmental conditions (Ligarreto-Moreno, 2017).

Yield can be affected by factors such as genotype (Colodetti *et al.*, 2015), agronomic management (Debela Bote and Vos, 2017), planting density (Sakai *et al.*, 2015), changes in the leaf-to-fruit ratio (Chaves *et al.*, 2012), and environmental resources such as radiation (Nesper *et al.*, 2017), water availability in the soil (Tesfaye *et al.*, 2014), physical, chemical, and microbiological characteristics of the soil (Bagyaraj *et al.*, 2015; Blanco-Sepulveda and Aguilar-Carrillo, 2015; Silva *et al.*, 2015), and fertilization (Melke and Ittana, 2014). Therefore, nutrition plays an essential role in crop yield because it participates in several physiological processes such as photosynthesis, assimilate partitioning, and respiration (Marschner, 2012).

Chemical synthesis fertilizers provide an immediate response to nutrient deficiencies in soil (Gentili *et al.*, 2006). However, these chemical fertilizers are expensive and most small-scale farmers cannot use them (Kawaka *et al.*, 2018). Given these circumstances, the combined use of lower amounts of organic and inorganic nutrients, such as compost, generates an alternative for restoring soil fertility, which is an affordable option for farmers in productive systems with scarce resources (Abegaz and van Keulen, 2009). These strategies play a key role in maintaining soil fertility and crop productivity in the tropics, supplying the nutrient requirements of plants with organic fertilizers such as plant residues, manure, and compost (Šimon and Czako, 2014).

Plants can uptake nutrients through their leaves, along with other growth-promoting substances (hormones, carbohydrates, and amino acids) at appropriate concentrations (Díaz-Leguizamón *et al.*, 2016). Foliar fertilization has been used to efficiently apply macronutrients, micronutrients, and humic substances because it favors nutrient assimilation in the plant, thus increasing crop yield and quality (Tejada *et al.*, 2018). This results in positive effects on the plant, mainly at physiological (both in respiration and photosynthesis), morphological (in root length and leaf area index), and yield levels (Tejada *et al.*, 2016).

Determining growth rates provides a quantitative approach to understanding the growth of a plant or population of plants under different cultivation practices, such as the fertilizer application method or the effect of fertilizers (Gil and Miranda, 2007). Growth rates such as relative growth rate (RGR) and absolute growth rate (AGR) have been used to model the effectiveness of fertilization treatments (Neuberg *et al.*, 2010). Therefore, the objective of this study was to evaluate the growth and yield of bush beans (*P. vulgaris* L.) under different integrated plant nutrient management (IPNM) strategies in the three Andean zones.

Materials and Methods

Plant material and growth conditions

Bean (*P. vulgaris* L.) seeds of the cultivar ‘Bacatá’ (bush growth habit (Type I) with six years of commercial release and biofortified with iron (Fe) and zinc (Zn)) were sown in 22.4 m² plots (four rows of eight linear meters long) in three different municipalities of the Department of Cundinamarca, Colombia: i) the municipality of Gachalá, Region of Guavio, located at an altitude of 1,800 m above mean sea level (4°39' N, 73°30' W) from August to December 2016; and ii) the municipality of Guachetá, Region of Ubaté, located at an altitude of 2,563 m above mean sea level (5°20' N, 73°43' W) from April to August 2016; and iii) in the greenhouse of the Faculty of Agricultural Sciences of Universidad Nacional de Colombia, located in the city of Bogotá at an altitude of 2,556 m above mean sea level (4°35' N, 74°04' W) from August to December 2016. Seeds were sown at 16 × 70 cm between plants and rows (200 seeds per plot, at a density of 85,000 plants ha⁻¹).

Gachalá: The physicochemical characteristics of the soil were as follows: i) clay loam texture: 31% sand, 34% silt, and 35% clay, ii) chemical characteristics, total nitrogen: 0.58%, Ca: 7.34 cmol (+) kg⁻¹, K: 0.47 cmol (+) kg⁻¹, Mg: 1.11 cmol (+) kg⁻¹, Na: 0.07 cmol (+) kg⁻¹, Cu: 0.75 mg kg⁻¹, Fe: 220 mg kg⁻¹, Mn: 2.42 mg kg⁻¹, Zn: 0.99 mg kg⁻¹, B: <0.12 mg kg⁻¹, and P: 17.3 mg kg⁻¹ iii) pH: 4.7, and iv) Effective Cation Exchange Capacity (ECEC): 11.1 cmol (+) kg⁻¹. The growth conditions during the assessment were as follows: average temperature, 18.2 °C; precipitation, 634 mm; relative humidity, 88%; and solar radiation, 14.6 MJ m⁻² per day.

Guachetá: The physicochemical characteristics of the soil were as follows: i) clay texture: 26% sand, 24% silt, and 50% clay, ii) chemical characteristics, total nitrogen: 0.30%, Ca: 12.7 cmol (+) kg⁻¹, K: 3.40 cmol (+) kg⁻¹, Mg: 6.27 cmol (+) kg⁻¹, Na: 0.30 cmol (+) kg⁻¹, Cu: 3.65 mg kg⁻¹, Fe: 409 mg kg⁻¹, Mn: 20.5 mg kg⁻¹, Zn: 23.6 mg kg⁻¹, B: 0.18 mg kg⁻¹, and P: 17.8 mg kg⁻¹, iii) pH: 5.3, and iv) ECEC: 23.0 cmol (+) kg⁻¹. The growth conditions during the assessment were as follows: average temperature, 15.4 °C; precipitation, 273 mm; relative humidity, 78%; and solar radiation, 16.7 MJ m⁻² per day.

Greenhouse: The physicochemical characteristics of the soil in the greenhouse were the following: i) clay loam texture: 26% sand, 42% silt, and 32% clay, ii) chemical characteristics, total Nitrogen: 0.36%, Ca: 10.6 cmol (+) kg⁻¹, K: 0.98 cmol (+) kg⁻¹, Mg: 1.75 cmol (+) kg⁻¹, Na: 0.24 cmol (+) kg⁻¹, Cu: 1.67 mg kg⁻¹, Fe: 310 mg kg⁻¹, Mn: 3.21 mg kg⁻¹, Zn: 15.5 mg kg⁻¹, B: 0.48 mg kg⁻¹, and P: >116 mg kg⁻¹, iii) pH: 5.4, and iv) ECEC: 13.8 cmol (+) kg⁻¹. The growth conditions in the greenhouse during the assessment were as follows: average temperature, 19.5 °C; water irrigation, 412 mm; relative humidity, 74%; and solar radiation, 14.2 MJ m⁻² per day.

Integrated plant nutrient treatments

After soil preparation, plants were subjected to six different nutrient treatments. Fertilization treatments and quantities are summarized in Table 1. The manufactures, the soil fertilizer, foliar fertilizer, compost made from grass and tree pruning residues, and commercial compost (soil aid) composition were the following: i) **edaphic fertilizer**, 18 N-46 P-0 K compound fertilizer (DAP[®], Yara, Colombia) as a source of nitrogen and phosphorus, 46 N- 0 P- 0 K simple fertilizer as nitrogen supplement (UREA[®], Yara, Colombia), and 0 N- 0 P- 60 K simple fertilizer as potassium supplement (KCl[®], Yara, Colombia); ii) **foliar fertilizer** (Nutrimins[®], Colinagro, Colombia), the synthesis was as follows: pH: 5 in a 10% solution, density at 20 °C: 1.135 g L⁻¹, total Nitrogen (N): 200 g L⁻¹, urea nitrogen (N): 200.0 g L⁻¹, magnesium (MgO): 2.5 g L⁻¹, total sulfur (S): 5 g L⁻¹, boron (B): 0.3 g L⁻¹, copper (Cu): 0.25 g L⁻¹, iron (Fe): 1 g L⁻¹, manganese (Mn): 0.55 g L⁻¹, molybdenum (Mo): 0.03 g L⁻¹, zinc (Zn): 1.6 g L⁻¹, and 1-Naphthylacetic acid (NAA): 0.5 g L⁻¹; iii) **green compost**, made from grass and tree pruning wastes in the greenhouses of the Universidad Nacional de Colombia with a humid base were the following: humidity percentage: 59.72%, bulk density: 0.47 g cm⁻³, Cation Exchange Capacity (CEC): 33.38 cmol(+) kg⁻¹, organic carbon: 14.36%, organic matter: 31.16%, C:N ratio: 15.5 (w:w), pH: 5.1, electrical conductivity: 15.84 dS m⁻¹, total nitrogen (N): 0.93%, ammoniacal nitrogen (NH₄): 0.039%, nitric nitrogen (NO₃): 0.006%, phosphorus (P): 0.22%, potassium (K): 0.6%, calcium (Ca): 0.81%, magnesium (Mg): 0.07%, sulfur (S): 0.11%, sodium (Na): 0.189%, iron (Fe): 1038.8 mg kg⁻¹, manganese (Mn): 34.9 mg kg⁻¹, copper (Cu): 7.4 mg kg⁻¹, zinc (Zn): 14.7 mg kg⁻¹, and boron (B): 6.8 mg kg⁻¹; and iv) **commercial compost**, the humid- based synthesis of the commercial compost (Soil Aid, Gestión Orgánica, Colombia) was as follows: maximum humidity: <13%, bulk density: 0.6 g cm⁻³, CEC: >53 cmol(+) kg⁻¹, organic carbon: >19%, organic matter: >1.4%, C:N ratio: >10 (w:w), pH: 7.0-8.0, total nitrogen (N): >1.4%, total phosphorus (P₂O₅): >2.5%, total potassium (K₂O): >3.0%, calcium (CaO): >3.8%, magnesium (MgO): 0.9%, iron (Fe): 1.2%, manganese (Mn): 378 mg kg⁻¹, copper (Cu): 953 mg kg⁻¹, zinc (Zn): 2262 mg kg⁻¹, boron (B): 59 mg kg⁻¹, and total organic silicon (SiO₂): >41%.

Both compost (green vs. commercial) and edaphic fertilizers (DAP and KCl) were supplied to the sown seeds. Urea application was equally split twice at 15 and 30 days after emergence (DAE). Finally, foliar applications were performed between 08.00 and 10.00 h at 50, 65, and 80 DAE using a backpack sprayer wetting both the upper and lower sides.

Table 1. Description of plant nutrition treatments used in the experiment

Treatment	Nomenclature	Fertilization
Absolute control	AC	Without fertilizer application
Edaphic fertilization control	EC	1.1 g DAP (70 kg ha ⁻¹); 1.2 g Urea (80 kg ha ⁻¹) and 0.8 g KCl (50 kg ha ⁻¹) plant ⁻¹
Green compost 20% +EC 80% + Foliar fertilization	GCCF	0.9 g DAP (56 kg ha ⁻¹); 1.0 g Urea (64 kg ha ⁻¹) and 0.6 g KCl (40 kg ha ⁻¹) plant ⁻¹ + compost made from grass and tree pruning residues at a dose of 8 g plant ⁻¹ (700 kg ha ⁻¹ corresponding to 20% of the recommended dose) with three applications of foliar fertilizer at a dose of 5 mL L ⁻¹ H ₂ O
Green compost 20% + EC 80%	GC	0.9 g DAP (56 kg ha ⁻¹); 1.0 g Urea (64 kg ha ⁻¹) and 0.6 g KCl (40 kg ha ⁻¹) plant ⁻¹ + compost made from grass and tree pruning residues at a dose of 8 g plant ⁻¹ (700 kg ha ⁻¹ corresponding to 20% of the recommended dose)
Commercial compost + EC 80% + Foliar fertilization	CCCF	0.9 g DAP (56 kg ha ⁻¹); 1.0 g Urea (64 kg ha ⁻¹) and 0.6 g KCl (40 kg ha ⁻¹) plant ⁻¹ + commercial compost (soil aid) at a dose of 4 g plant ⁻¹ (350 kg ha ⁻¹) with three applications of foliar fertilizer at a dose of 5 mL L ⁻¹ H ₂ O
Commercial Compost + EC 80%	CC	0.9 g DAP (56 kg ha ⁻¹); 1.0 g Urea (64 kg ha ⁻¹) and 0.6 g KCl (40 kg ha ⁻¹) plant ⁻¹ + commercial compost (soil aid) at a dose of 4 g plant ⁻¹ (350 kg ha ⁻¹)

Dry matter accumulation, leaf area, and growth indices

Total dry matter, leaf area, specific leaf area, stem diameter, and shoot length were determined for five plants per treatment in each replicate at 45, 52, 59, 66, and 73 DAE. Leaf area was calculated from digital images obtained using Java image-processing software (Image J; National Institute of Mental Health, Bethesda, MD, USA). The plants were then dried in a compressed dry air oven (ThelcoMod 27, Chicago, IL, USA) at 80 °C for 48 h to obtain the total dry weight of the plant.

To determine the growth components, the Leaf Area Index (LAI), Leaf Area Ratio (LAR), Relative Growth Rate (RGR), and Net Assimilation Rate (NAR) were calculated using the following equations proposed by Carranza *et al.* (2009):

$$\text{LAI} = L_A/P; \text{ (Adimensional)} \quad (1)$$

$$\text{LAR} = L_A/W; \text{ (cm}^2 \text{ g}^{-1}\text{)} \quad (2)$$

$$\text{RGR} = (1/W) (dW/dt); \text{ (g g}^{-1} \text{ d}^{-1}\text{)} \quad (3)$$

$$\text{NAR} = (1/L_A) (dW/dt); \text{ (g cm}^{-2} \text{ d}^{-1}\text{)} \quad (4)$$

where W is total dry matter (g), L_A is leaf area (cm²), P=Leaf area per unit of soil surface (cm²), and dW/dt is dry matter variation as a function of time.

Yield parameters and agronomic efficiency

Five plants per experimental unit were selected to obtain the yield components. The grains in each treatment were harvested at the end of the crop cycle (between 145 and 155 DAE) (approximately 14% humidity). The following yield components were estimated: number of grains per pod recorded in 20 pods,

number of pods per plant, yield per plant, 100-grain weight, and yield per hectare, based on the number of plants per plot and weight per plant. Agronomic efficiency was calculated following the methodology proposed by Xu *et al.* (2014), which consisted of the ratio between the nutrition treatment and the absolute treatment without fertilization, considering the yield data per hectare.

Experimental design and data analysis

At each of the three locations (Gachalá, Guachetá, and Greenhouse), an experiment was conducted to compare the six nutrition treatments (Table 1). A randomized block design, with four replicates in the same planting year, was used at each location. The data from the experiments were analyzed by series of experiments to determine the effect of the interaction of locations × treatments (Fernández-Escobar *et al.*, 2018). When significant differences were obtained in ANOVA, Tukey's mean comparison test was used at $P \leq 0.05$. Data were analyzed using Statistix v 9.0 (analytical software, Tallahassee, FL, USA).

Results

Highly significant statistical differences ($P \leq 0.01$) were observed between evaluation locations, nutrition treatments, and for the interaction between locations × treatments, except in the nutrition treatments for yield components such as pods per plant and grains per pod that did not show statistical differences, and for yield per plant and weight of 100 grains that reached significant differences ($P \leq 0.05$) (Table 2). The results of the different response variables are presented based on location and nutrition treatments. In the case of dry matter accumulation, leaf area, and growth rate, the data are presented as days after emergence.

Table 2. Variance components in the growth and yield of bush beans with different nutrition treatments at three locations

Source	Leaf area (cm ²)	Total dry matter (g)	LAI	LAR (cm ² g ⁻¹)	RGR (g g ⁻¹ d ⁻¹)	AGR (g cm ⁻² d ⁻¹)
Locations (L)	***	***	***	**	**	**
Treatments (T)	**	***	***	**	**	**
L x T	*	**	*	**	**	**
Source	Pods plant ⁻¹	Grains pod ⁻¹	Yield plant ⁻¹	Weight of 100 grains (g)	Yield (kg ha ⁻¹)	Agronomic efficiency (%)
Locations (L)	**	**	**	**	**	**
Treatments (T)	ns	ns	*	*	**	**
L x T	ns	*	**	*	**	**

LAI = Leaf Area Index, LAR = Leaf Area Ratio, RGR = Relative Growth Rate and AGR = Absolute Growth Rate. ns, *, **, and ***= not significant, significant at $P \leq 0.05$, very significant at $P \leq 0.01$, and highly significant at $P \leq 0.001$, respectively.

Leaf area and dry matter accumulation

The results of leaf area and dry matter accumulation of bush bean plants subjected to different fertilization treatments are shown in Figures 1, 2, and 3. Figure 1A shows that significant differences were observed among the locations evaluated at 45, 52, 59, 66, and 73 DAE. Plants were mainly sown in the greenhouse, and Guachetá exhibited the highest leaf area values up to 52 DAE. However, from 59 DAE, plants under greenhouse conditions showed the largest leaf area until the end of the evaluation period, reaching an

increase of approximately 20% and 60%, respectively, compared to those obtained in the localities of Guachetá and Gachalá at 73 DAE. Regarding the integrated plant nutrient treatments, significant differences were found among the five evaluation points (Figure 1b). The absolute control (AC) treatment had the lowest leaf area. Additionally, the plants with the application of nutrients showed an increase in this variable, with edaphic control (EC), compost of grass pruning residues with foliar fertilization (GCFF), and without foliar fertilization (GC), which exhibited higher values throughout the experiment compared to the absolute control (AC), especially at 73 DAE, with an increase close to 43%. Soil-aid commercial compost treatments with foliar fertilization (CCFF) and without foliar fertilization (CC) increased leaf area by 19% and 28%, respectively, compared to plants without nutrients.

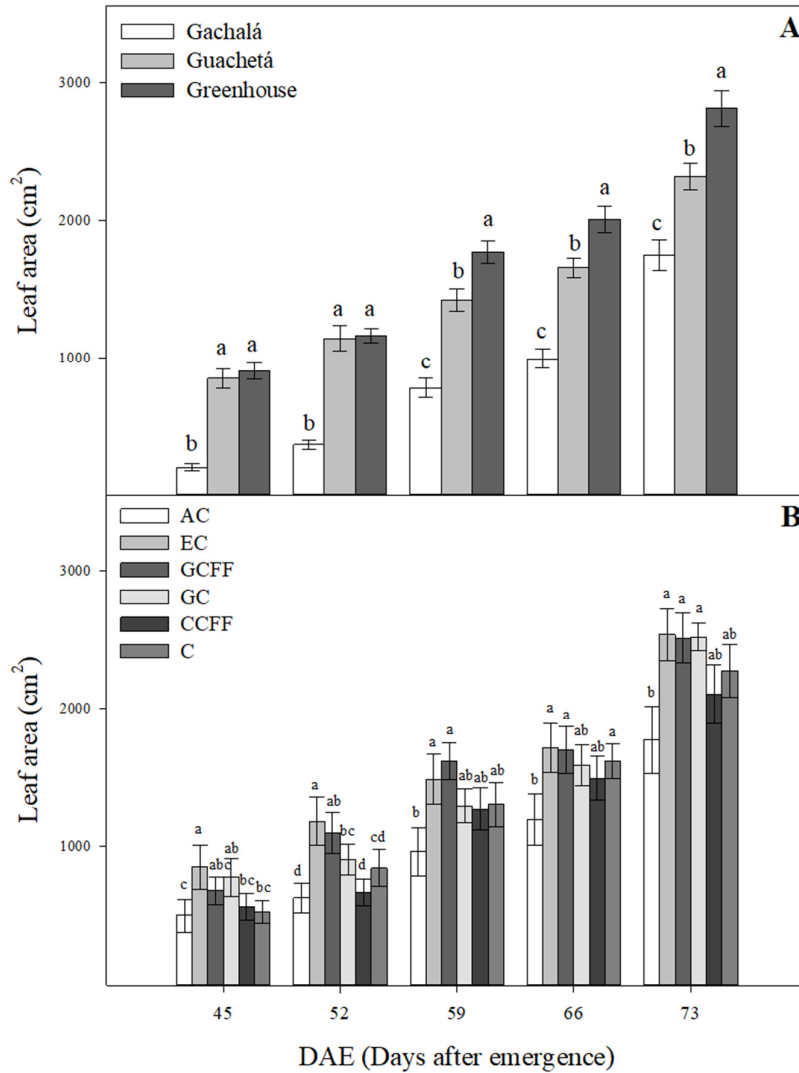


Figure 1. Effects of the factors localities (Gachalá, Guachetá and greenhouse) **(A)** and integrated plant nutrient treatments (AC: absolute control, EC: edaphic control, GCFF: green compost + EC 80% + Foliar fertilization, GC: green compost + EC 80%, CCFF: commercial compost + EC 80% + Foliar fertilization, CC: commercial compost + EC 80%) **(B)** on the leaf area of bush bean (*Phaseolus vulgaris* L.) plants at 45, 52, 59, 66 and 73 days after emergence (DAE)

Means within the sampling point followed by the same letter are not significantly different according to Tukey's test ($P < 0.05$).

Figure 2 summarizes the results of dry matter accumulation at the evaluated locations. The municipality of Gachalá had the highest dry matter values at 73 DAE (Figure 2a), followed by the plants in the greenhouse (Figure 2c) and the municipality of Guachetá (Figure 2b). It was also found that the plants from Gachalá and the greenhouse began flowering at 52 DAE, whereas for plants in Guachetá, this stage was not evident during the evaluation period. Additionally, the municipality of Gachalá showed higher dry matter accumulation than plants under greenhouse conditions, reaching values of 14.1 g plant⁻¹ and 10.8 g plant⁻¹, respectively.

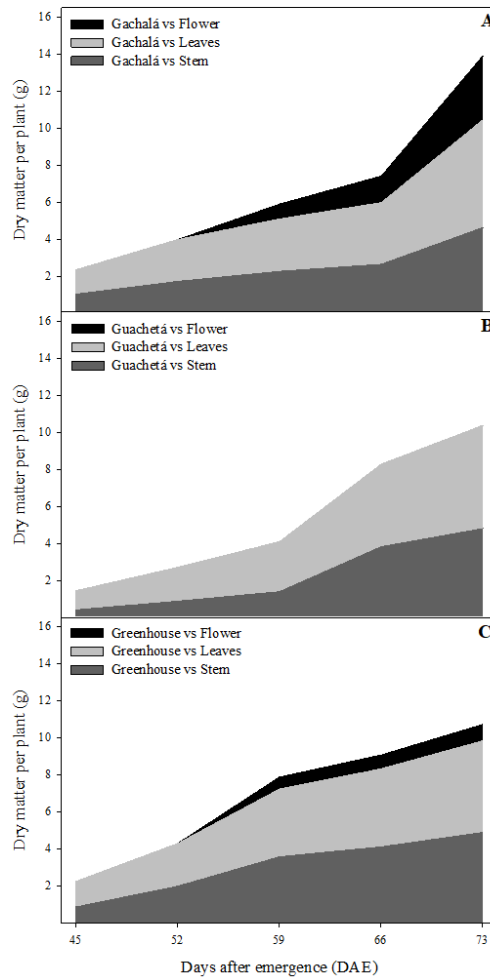


Figure 2. Dry stems, leaves and flower matter accumulation of bush bean (*Phaseolus vulgaris* L.) plants according to the factor localities [(A) Gachalá; (B) Guacheta; (C) Greenhouse] at 45, 52, 59, 66 and 73 days after emergence (DAE)

Figure 3 shows dry matter accumulation from the integrated plant nutrient treatments in bush bean plants. Plants in the AC and CC treatments had the lowest dry matter content at the end of the experiment (~9.2 g plant⁻¹). EC plants had the highest dry matter accumulation at 73 DAE (60%), followed by GCFF and GC, which showed increases of 44% and 43%, respectively, compared with the plants in the absolute control. However, the GC plants showed the highest dry matter accumulation in the flowers throughout the experiment, with flowering beginning 45 DAE. This treatment reached a significant increase in the dry matter accumulation at the end of the experiment compared to AC plants (2.35 g plant⁻¹ vs. 0.20 g plant⁻¹, respectively), while the other treatments started this stage at 52 DAE, with dry matter accumulation of approximately 1.8 g plant⁻¹.

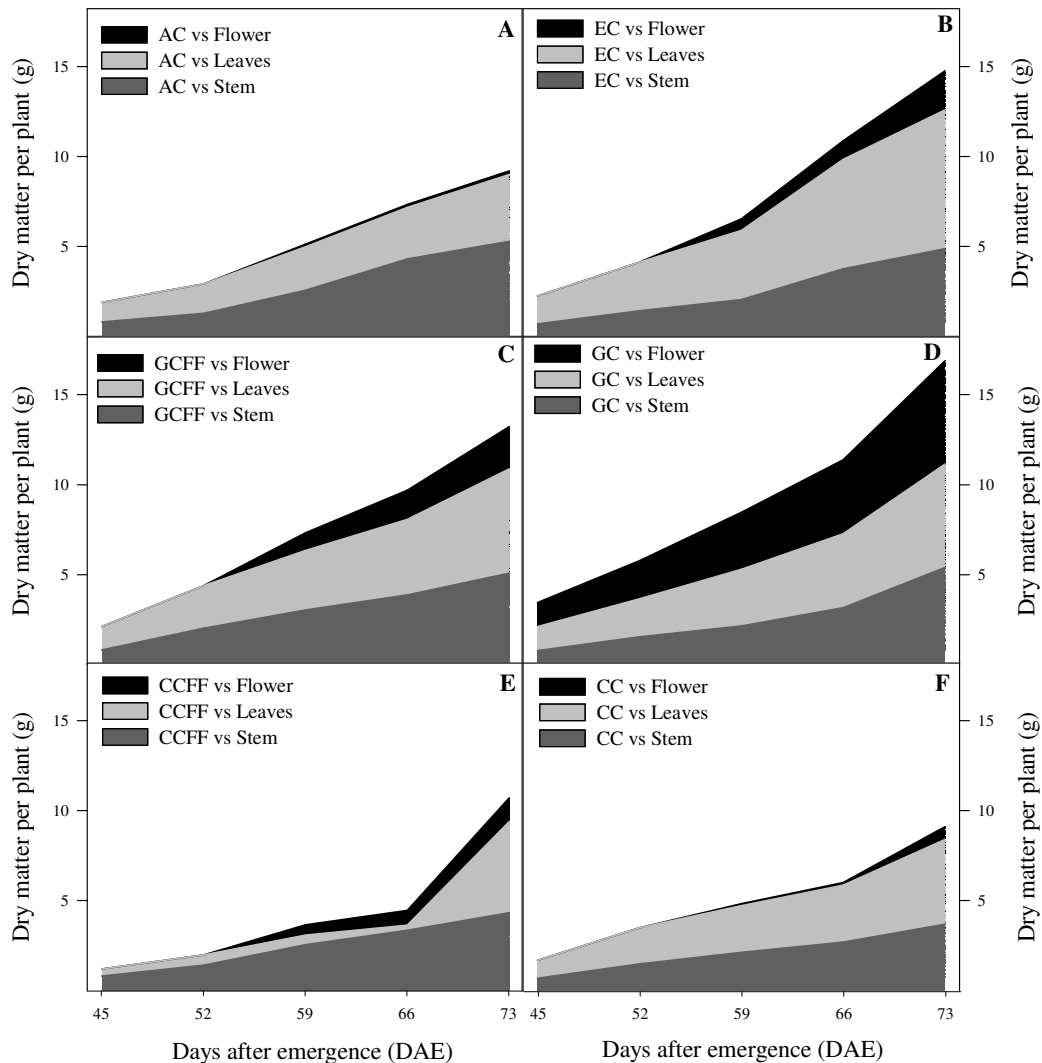


Figure 3. Dry stem, leaf, and flower matter accumulation of bush bean (*Phaseolus vulgaris* L.) plants according to the factor integrated plant nutrient treatments [AC: absolute control (A), EC: edaphic control (B), GCFE: green compost + EC 80% + foliar fertilization (C); GC: green compost + EC 80% (D); CCFF: commercial compost + EC 80% + foliar fertilization (E), CC: commercial compost + EC 80% (F)] at 45, 52, 59, 66, and 73 days after emergence (DAE)

Growth rates

Figure 4 summarizes the significant differences in Leaf Area Index (LAI) and Leaf Area Ratio (LAR) between locations and integrated plant nutrient treatments in Bacatá bean plants. An increasing trend was observed in the LAI values with respect to evaluation time, whereas the LAR showed a reduction in values as the plants grew. Additionally, the town of Gachalá had the lowest LAI and LAR values at the different sampling points (Figure 4a and c). However, at 73 DAE, Bacatá bean plants reached the highest LAI values when sown in the greenhouse (~1.7), whereas plants from Guachetá registered an approximate value of ~1.4. This trend was maintained for the LAR, being the plants of the Greenhouse and the town of Guachetá those that showed the highest increase of this variable compared to the plants located in the municipality of Gachalá (305.93 cm² g⁻¹, 495.00 cm² g⁻¹ and 578.19 cm² g⁻¹, respectively). Regarding integrated plant nutrient treatments, an increase

in LAI and LAR was observed in fertilized plants compared to those that were not supplied with nutrients. An increase in LAI of approximately 42% for the EC, GCFF, and GC treatments compared with AC plants was observed at 73 DAE. Finally, LAR showed differences from 59 DAE between the integrated plant nutrient treatments, with a higher LAR in CC plants. This trend was maintained until the end of the experiment (Figure 4b and d).

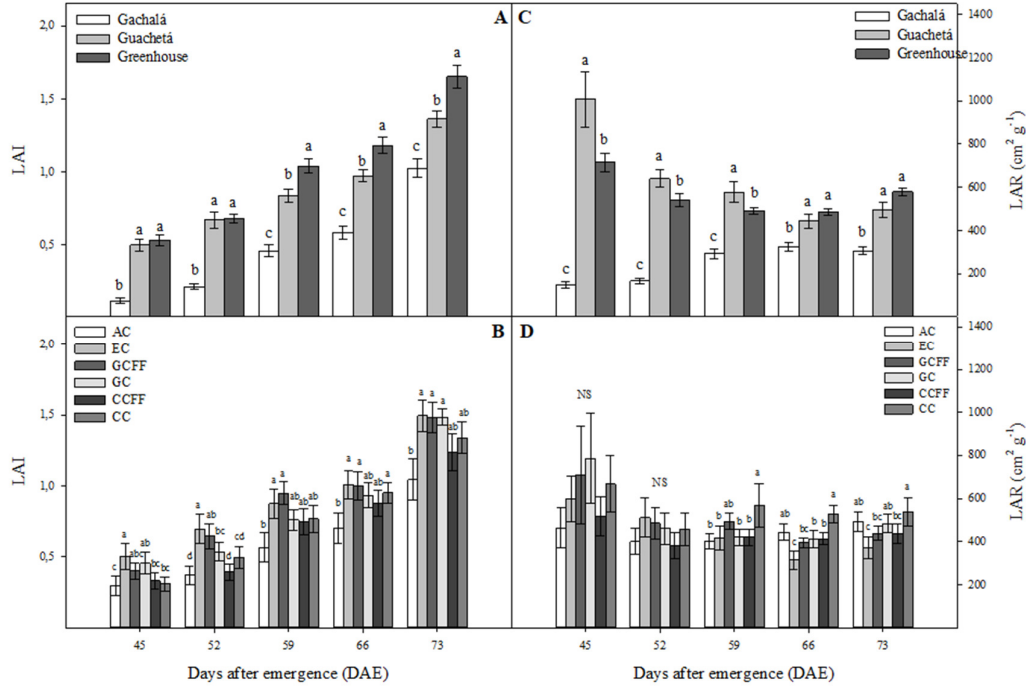


Figure 4. Effects of the factors localities (Gachalá, Guachetá and greenhouse) (**A, C**) and integrated plant nutrient treatments (AC: absolute control, EC: edaphic control, GCFF: green compost + EC 80% + Foliar fertilization, GC: green compost + EC 80%, CCFF: commercial compost + EC 80% + Foliar fertilization, CC: commercial compost + EC 80%) (**B, D**) on Leaf Area Index (LAI) (**A, B**) and Leaf Area Ratio (LAR) (**C, D**) of bush bean (*Phaseolus vulgaris* L.) plants at 45, 52, 59, 66 and 73 days after emergence (DAE). Means within the sampling point followed by the same letter are not significantly different according to Tukey's test ($P < 0.05$). NS: Non-significant.

Figure 5 shows the significant differences in the Relative Growth Rate (RGR) and Absolute Growth Rate (AGR) between locations and nutrition treatments in Bacatá bean plants. At 73 DAE, the town of Gachalá registered the highest RGR value (0.095 g cm^{-2} per day), followed by the town of Guachetá and the greenhouse (0.032 and 0.024 g cm^{-2} per day, respectively) (Figure 5a). This trend was maintained for the AGR, being the plants from Gachalá those that obtained the highest values for this variable (0.68 g cm^{-2} per day) (Figure 5c). Regarding integrated plant nutrient treatments, GC and CC plants exhibited the highest increases in RGR ($\sim 120\%$ and $\sim 73\%$, respectively) compared to AC plants (Figure 5b). A similar trend was observed in the AGR, with the GC treatment registering the highest value (0.12 g cm^{-2} per day) compared to the plants of the absolute control (0.04 g cm^{-2} per day) (Figure 5d).

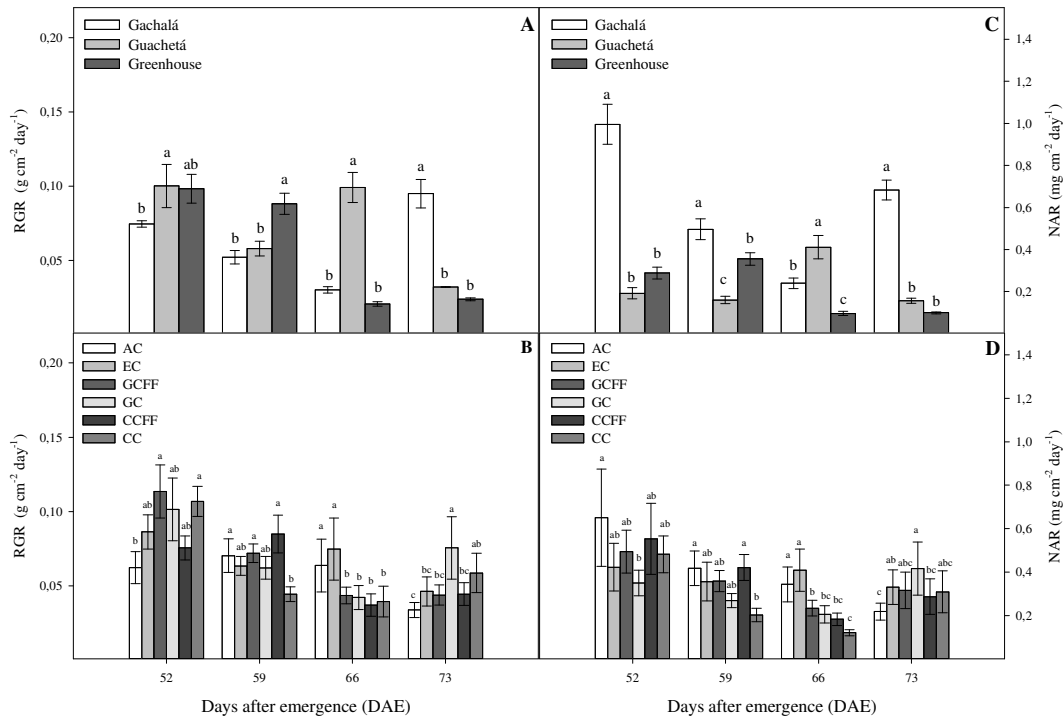


Figure 5. Effects of the factors localities (Gachalá, Guachetá and greenhouse) (A, C) and integrated plant nutrient treatments (AC: absolute control, EC: edaphic control, GCFF: green compost + EC 80% + Foliar fertilization, GC: green compost + EC 80%, CCFF: commercial compost + EC 80% + Foliar fertilization, CC: commercial compost + EC 80%) (B, D) on Relative Growth Rate (RGR) (A, B) and Absolute Growth Rate (AGR) (C, D) of bush bean (*Phaseolus vulgaris* L.) plants at 52, 59, 66 and 73 days after emergence (DAE)

Means within the sampling point followed by the same letter are not significantly different according to Tukey's test ($P \leq 0.05$).

Yield parameters and agronomic efficiency

Significant differences were observed in the yield parameters of ‘Bacatá’ bean plants between the evaluated locations and integrated plant nutrient treatments (Figure 6 and 7). Plants sown in the greenhouse had the lowest number of pods per plant (~6), yield per plant (~15 g), and yield per hectare (~1000 kg ha⁻¹) (Figure 6a, c, and e). Additionally, the grains from the localities of Gachalá and Guachetá were larger than those harvested in the greenhouse, reaching a 100-grain weight close to 60 g, compared to the 50 g observed in the greenhouse. However, the locality with the highest yield was Gachalá, with an increase of 18% compared to the locality of Guachetá and 118% higher than that of greenhouse plants (Figure 6d). Regarding the integrated plant nutrient treatments, significant differences were found in yield per plant, yield per hectare, and 100-grain weight (Figure 7). In summary, plants without any nutrient application showed the lowest yield parameters compared to the other treatments, reaching a production of approximately 1100 kg ha⁻¹ (Figure 7c). Additionally, regardless of the integrated plant nutrient treatments, the grains harvested from Bacatá bean plants were larger than those from plants without nutrients, reaching a 100-grain weight of close to 60 g (Figure 7b). This trend was maintained in the yield per plant and hectare, reaching a production of approximately 36.7 kg plant⁻¹ and 1600 kg ha⁻¹, respectively (Figure 7a and c).

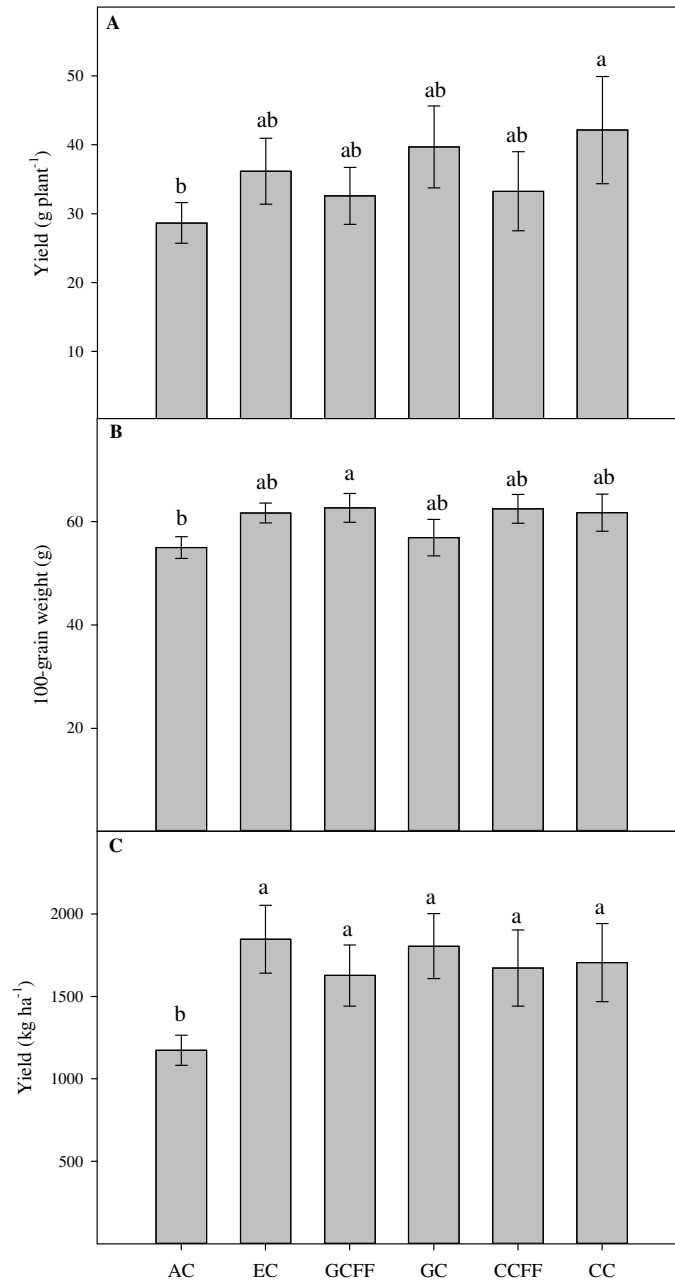


Figure 6. Yield parameters of bush bean (*Phaseolus vulgaris* L.) plants such as number of pods per plant (A); number of grains per pod (B); yield per plant (C); 100-grain weight (D); and yield per hectare (E) according to the factor localities (Gachalá, Guachetá and greenhouse) at harvest. For all treatments, the values represent the mean of four replicates \pm the standard error. Means within the sampling point followed by the same letter are not significantly different according to Tukey's test ($P \leq 0.05$).

Significant differences in the agronomic efficiency (AE) of bean crops between locations and nutrition treatments are shown in Figure 8. Plants from Guachetá had the highest AE values ($\sim 170\%$), followed by those from the town of Gachalá ($\sim 140\%$), and the greenhouse ($\sim 103\%$) (Figure 8a). Regarding the integrated plant nutrient treatments, it was evident that the town of Gachalá had the lowest AE values in the CCFF treatment plants ($\sim 100\%$), whereas the other treatments had values over $\sim 150\%$. (Figure 8b). However, the CCFF

treatment reached an AE close to 240% in Guachetá, with the highest value recorded among the three evaluated localities (Figure 8c). ‘Bacatá’ bean plants sown in the greenhouse had the lowest AE values, especially in the CCFF and CC treatments (~80%) (Figure 8d).

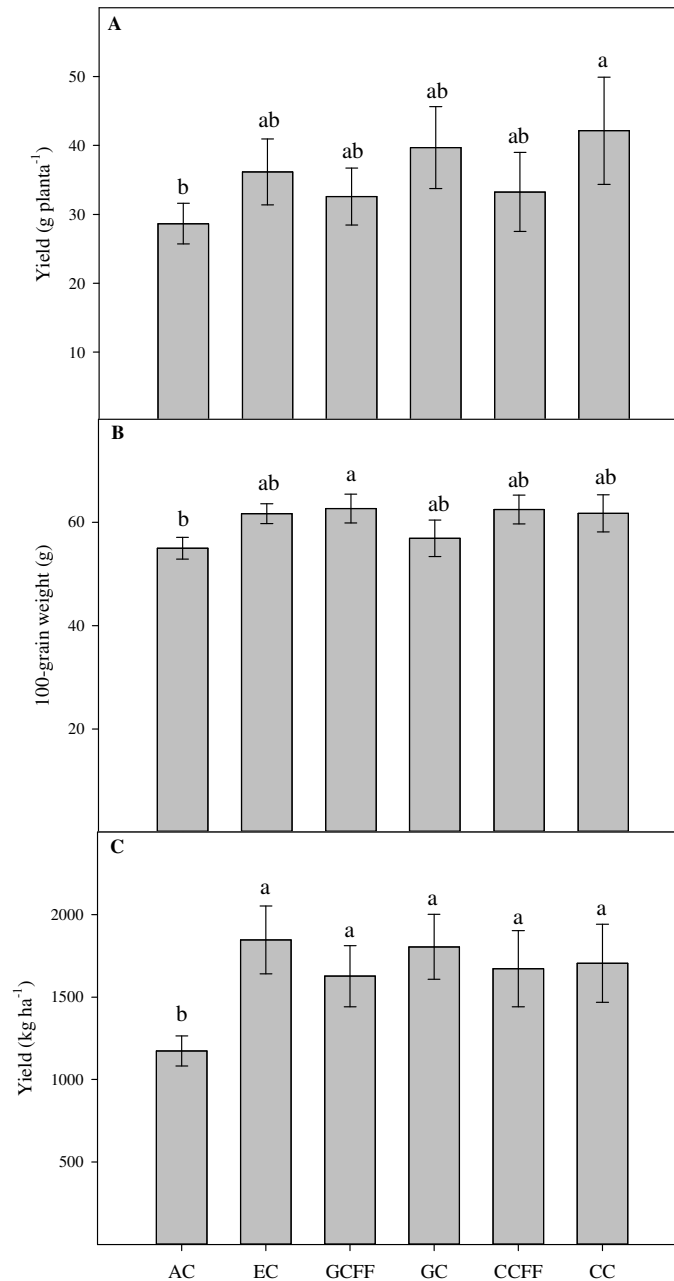


Figure 7. Yield parameters of bush bean (*Phaseolus vulgaris* L.) plants such as yield per plant (A); 100-grain weight (B); and yield per hectare according to the factor integrated plant nutrient treatments (AC: absolute control, EC: edaphic control, GCFF: green compost + EC 80% + foliar fertilization, GC: green compost + EC 80%, CCFF: commercial compost + EC 80% + foliar fertilization, CC: commercial compost + EC 80%) at harvest

Means within the sampling point followed by the same letter are not significantly different according to Tukey's test ($P \leq 0.05$).

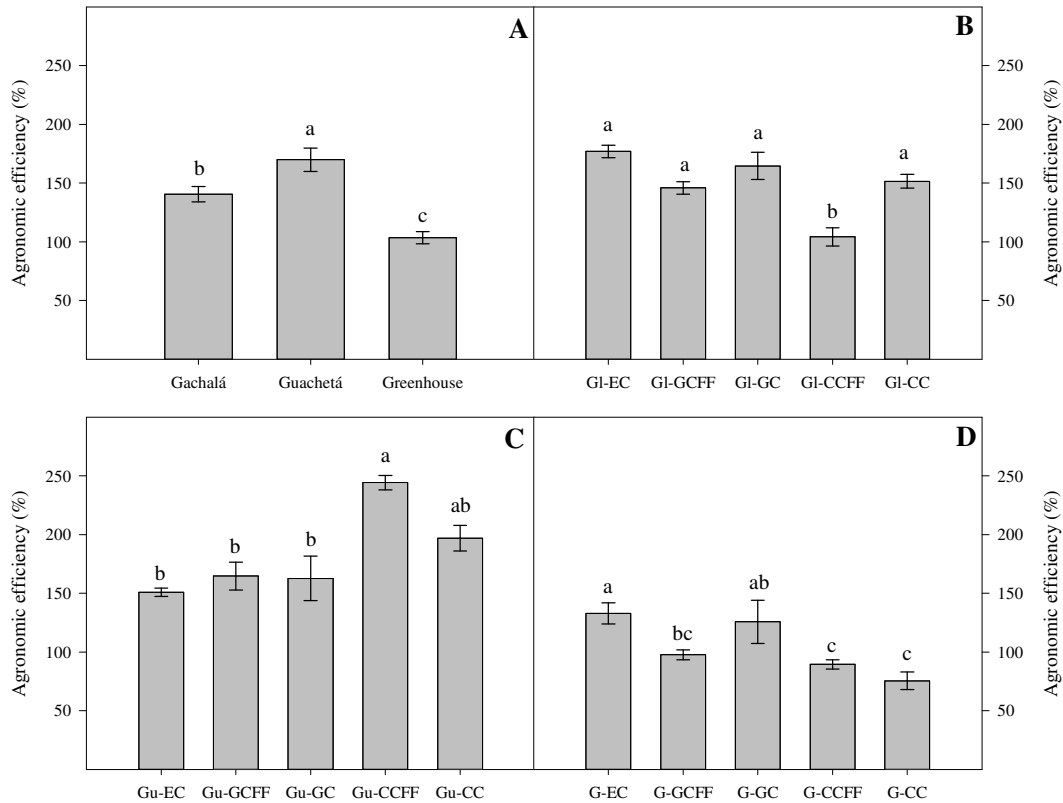


Figure 8. Agronomic efficiency of bush bean (*Phaseolus vulgaris* L.) in three locations (Gachalá, Guachetá and greenhouse) (A) and the interaction between integrated plant nutrient treatments (EC: edaphic control, GCFF: green compost + EC 80% + Foliar fertilization, GC: green compost + EC 80%, CCFF: commercial compost + EC 80% + Foliar fertilization, CC: commercial compost + EC 80%) and locations (Gachalá (Gl) (B), Guachetá (Gu) (C) and greenhouse (G) (D) at harvest. Means within the sampling point followed by the same letter are not significantly different according to Tukey's test ($P \leq 0.05$).

Discussion

Foliar fertilization and compost application have been used as strategies to supply nutrients to plants and improve crop productivity (Ho *et al.*, 2022; Pimentel *et al.*, 2023). Positive effects of the mutual application of compost and foliar sprays have been reported in crops (Abo-Steet *et al.*, 2015; Nemeat-Alla *et al.*, 2019). Studies have focused mainly on the growth parameters, yield components, and agronomic behavior of common bean crops in Colombian high Andean zones (White and Montes-R, 2005; Ligarreto-Moreno and Pimentel-Ladino *et al.*, 2021). However, little is known about the effects of the interaction between plant nutrition strategies, including joint compost and foliar fertilization, on the yield, growth, and development of bush bean plants in different high-Andean zones. Kyei-Boahen *et al.* (2017) stated that applying the same fertilization program throughout different zones cannot cause the same crop response, such as yield and dry matter accumulation.

The three environments caused differential responses in the growth parameters throughout the study. The region with a higher rainfall (Gachalá) generally showed that growth indices such as RGR and AGR were higher, whereas LAI and LAIR were lower than those in the low rainfall zone (Gachetá) and greenhouse at different sample points. Wright and Westoby (1999) mentioned that the RGR would decrease from high to

low rainfall, and this reduction is associated with a low LAR. This was also observed in the present study. However, canopy interception loss can be associated with the higher LAI observed in low rainfall environments. Wang and Guo (2024) concluded that canopy interception loss increases with higher LAI and diminishes with increasing rainfall, suggesting that canopy interception plays an important role in crop production, especially with a small LAI and high precipitation.

It is also important to note that the use of chemical fertilizers with organic fertilizers caused growth similar to that of plants treated with only chemical fertilizers in this study. Abou-El-Hassan *et al.* (2017) reported that organic fertilizers enhance soil aeration, increase nutrient retention capacity, and offer good environmental conditions for roots, improving nutrient absorption, plant growth, photosynthetic activity, dry matter accumulation, and consequently, yield. Additionally, Yassen *et al.* (2020) found that the use of an organic compound (vermicompost) with foliar applications as a complement to mineral nutrition improved vegetative growth, as this type of combined treatment allowed for greater nutrient absorption by plants. We observed a similar trend, in which plants with applications of organic compounds (commercial compost [Soil Aid] or compost made with pruning residues) showed slight dry matter accumulation throughout the evaluation period, mainly in the low rainfall environment.

Differential agronomic behavior was also observed between the growing environments. In this study, 'Bacata' plants has a better yield component in the high rainfall Andean Zone than low rainfall zones. Studies carried out by Ligarreto *et al.* (2015) in phenotypic stability of shrub common bean, indicating that this kind of genotypes can have a low behavior in zones with low environmental index (water deficit regions) according to Eberhart and Russell (1966). Additionally, greenhouse studies showed that 'Bacata' plants showed a low Stress Tolerance Index (STI) when plants were exposed to water deficit or high temperatures (≥ 30 °C) (Chavez-Arias *et al.*, 2018; Sánchez-Reinoso *et al.*, 2020). The previous observations can help to support why 'Bacata' plants showed low yield component in low rainfall zone and greenhouse, since environmental conditions such as water availability and high temperatures could affect the crop performance.

The use of composted sources as crop fertilizers is a good alternative to inorganic fertilization for sustainable agriculture (Hernandez *et al.* 2016). In general, the application of the two compost compounds showed agronomic efficiency similar to that of plants treated with chemical fertilizers only. Al-Suhaibani *et al.* (2021) evaluated the integrated application of composted agricultural wastes, chemical fertilizers, and biofertilizers, and observed that this kind of nutritional strategy enhanced plant nutritional status and yield in maize. Additionally, Fu *et al.* (2023) reported that compost partial substitution fertilization can effectively improve soil fertility by improving the composition of the soil bacterial community and physicochemical properties (soil organic matter, total nitrogen, and available nitrogen and potassium).

Foliar fertilization is an effective method for increasing the content of elements in crops (Niu *et al.*, 2021). In addition, the use of chemical fertilizers with organic and foliar sprays can improve the physiological performance and productivity of plants (Mohamed *et al.* 2021). Growth parameters (plant height, dry weight, and leaf area) and yield components have been used to estimate the combination of soil application of organic (green or commercial compost), inorganic, and foliar fertilizers (El-Sobky, 2021; Mohamed *et al.*, 2021). In this study, it was observed that the combined soil application (organic and inorganic fertilizers) and foliar fertilization did not cause significant plant growth and yield compared to EC plants; however, this combined treatment (CCFF) induced higher agronomic efficiency in the low-rainfall Andean zone (Guachetá). The opposite results were observed by Ghazi (2020), in which combined soil green compost application and foliar fertilization caused differential responses in the growth and yield of hot pepper plants. This lack of response to foliar fertilization can be associated with climatic factors (rainfall or air temperature) or application factors (type of compound or rate), which could affect treatment effectiveness (Fernández *et al.*, 2013)

The results of this study are important for the bean production chain because they allow for the evaluation of different management alternatives for mineral nutrition of the crop and an understanding of the influence of the environment on the performance of the same alternatives in different localities, helping to

generate integrated plant nutrient management (IPNM) strategies to sustain crop production and improve the grower's income. Another advantage of this research is that the analysis of physiological behavior through the quantification of growth variables, yield parameters, and agronomic efficiencies helped to understand the effects of the environment and level of fertilization on the acclimatization of bean plants. The results obtained in this study provide information for consideration of different mineral nutrition plans for bean crops.

Conclusions

In conclusion, the use of growth and yield parameters is an important tool for estimating crop responses to integrated plant nutrient treatments in contrasting growing environments. The common bush bean growth was mainly conditioned by water availability, in which the zone with high rainfall expressed high growth and yield. The results obtained allow to suggest that the common bush bean growers can have different options to integrated plant nutrition management in which the compost (green or commercial) may be a complementary option in the management of mineral nutrition of common bush bean crop in high Andean regions. Compost applications can reduce the use of chemical fertilizers by at least 20%, thereby generating an affordable alternative for low- and lower-middle-income growers.

Authors' Contributions

Conceptualization: ADS-R, HR-D and GAL-M; Data curation: ADS-R and GAL-M; Formal Analysis: ADS-R and GAL-M; Funding acquisition: HR-D and GAL-M; Investigation: ADS-R, HR-D and GAL-M; Methodology: ADS-R; Project administration; HR-D and GAL-M; Resources: HR-D and GAL-M; Software: ADS-R and GAL-M; Supervision: HR-D and GAL-M; Validation: ADS-R; Visualization: ADS-R; Writing - original draft: ADS-R; Writing - review and editing: HR-D and GAL-M. All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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