



## Article

# Enhancing Sustainable Production of Borage Plant (*Borago officinalis* L.) through Synergy Between NPK Fertilization, Biostimulants, and Amino Acids

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**Abstract:** A field experiment was conducted at the field station of the Department of Horticulture and Landscape Design, College of Agriculture and Forestry, University of Mosul, during the 2025–2026 growing season. The experiment was designed according to a split-split plot arrangement within a Randomized Complete Block Design (RCBD) with three factors, three replicates, and ten plants per replicate. It aimed to evaluate the physiological and productive response of borage plants (*Borago officinalis* L.) to mineral fertilization with NPK, treatment with the Bio Health preparation, and spraying with amino acids, as well as to study the effect of binary and triple interactions among them on improving vegetative and root growth, flowering, yield, and some chemical traits of the plant. The results clearly showed that the plant's response did not depend on the effect of any single factor alone, but rather was the outcome of functional integration among mineral nutrition, biostimulants, and amino acids - a matter directly reflected in improving the plant's physiological performance and increasing its productive efficiency. Mineral fertilization with NPK improved most of the studied traits compared to the control, particularly at the 100 kg·ha<sup>-1</sup> level, which increased plant height, number of branches, leaf area, and number of leaves, reaching (96.46 cm, 21.68 branch·plant<sup>-1</sup>, 608.94 cm<sup>2</sup>·plant<sup>-1</sup>, and 89.00 leaf·plant<sup>-1</sup>), respectively. This was also reflected in improved number of flowers, flowering duration, and dry weight of the flower cluster, which increased to (3026.11 flower·plant<sup>-1</sup>, 74.02 days, 5.21 g), respectively. Furthermore, at the NPK level of 150 kg·ha<sup>-1</sup>, root growth was enhanced, with increased root length and dry weight, reaching (82.57 cm and 13.82 g), respectively. Total yield increased to 481.75 kg·ha<sup>-1</sup>, in addition to raising the concentration of estimated nutrients in the leaves - most importantly nitrogen, phosphorus, and potassium, whose average values reached approximately (2.63%, 0.31%, and 0.67%), respectively. The results also showed that using Bio Health at 3 kg·ha<sup>-1</sup> improved most growth and production indicators, confirming the effectiveness of this preparation as a biostimulant that raises the plant's metabolic activity, improves root-zone characteristics, increases nutrient availability, and

stimulates fine-root formation, leading to increased absorption efficiency and improved photosynthesis. This was reflected in increased plant biomass and improved flowering traits: number of flowers reached 2448.59 flower·plant<sup>-1</sup>, flowering duration increased to 64.03 days, and dry flower weight increased to 4.82 g. In addition, 100-seed weight and total yield increased to (1.91 g and 437.97 kg·ha<sup>-1</sup>), respectively. The study also proved that spraying with amino acids produced a distinct physiological response, manifested in a clear increase in vegetative and root growth indicators and improved flowering, productive, and chemical traits. This is attributed to the direct role of amino acids in the biosynthesis of proteins, enzymes, and plant hormones, particularly at 2.5 ml·L<sup>-1</sup>, at which stem diameter, leaf area, number of leaves, number of flowers, flowering duration, and total yield increased, reaching (9.73 mm, 492.73 cm<sup>2</sup>·plant<sup>-1</sup>, 84.33 leaf·plant<sup>-1</sup>, 2204.78 flower·plant<sup>-1</sup>, and 452.30 kg·ha<sup>-1</sup>). The binary and triple interactions showed that integration between mineral fertilization, Bio Health, and amino acids was more effective than any single factor alone, with some interaction treatments achieving the highest averages in most studied traits - whether related to vegetative growth, the root system, flowering, yield, or chemical traits. These results indicate a synergistic effect among the treatments: improved nutrient availability, increased absorption efficiency, and activation of vital processes within the plant raised nutrient-use efficiency and improved the distribution of photosynthates among the plant's organs, ultimately increasing production and improving its quality. Finally, the results obtained represent an important scientific contribution to the field of borage nutrition, clarifying the physiological mechanisms explaining the plant's response to the interaction between mineral fertilization, biostimulants, and amino acids. They provide scientific evidence that integrated fertilization management is not limited to increasing growth and production, but also contributes to improving the plant's physiological efficiency and its ability to exploit nutritional resources more effectively - opening the way for future studies evaluating the effect of these treatments on oil quality and active compounds in borage seeds, as well as their response under different environmental stress conditions, thereby supporting the development of more efficient and sustainable fertilization programs for medicinal and aromatic plants.

**Key words:** Borage plant, Fertilization NPK, Amino acids, Biostimulants, Productivity, Growth.

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## 1. Introduction

Borage (*Borago officinalis* L.) is an annual herb belonging to the family Boraginaceae, known by several local names in Arab countries such as Lisan al-Thawr, Borage, Hamham, and Hamham al-Makhzani, and in English as borage, common borage, and starflower. Its original home is the Mediterranean region (Slama *et al.*, 2024), and its cultivation later spread to many regions of Europe, Asia, and North America due to its nutritional, medicinal, and agricultural importance. The plant is characterized by its blue star-shaped flowers and coarse, hair-covered leaves, which give it aesthetic value and make it suitable for landscaping gardens and green spaces, in addition to its ability to adapt to different environmental conditions and grow in well-drained soils and temperate climates. The ecological importance of borage is highlighted by its abundant production of nectar and pollen, which makes it attractive to bees and pollinating insects, thereby contributing to increased biodiversity and improved pollination services within agricultural systems and gardens. It is also considered a plant that supports the sustainability of urban ecosystems and environmentally friendly agriculture, hence the growing interest in incorporating it into sustainable agriculture and pollinator conservation programs (Slama *et al.*, 2024; Stearn, 2020).

The increasing economic importance of borage is also attributed to its content of numerous bioactive compounds, such as phenolic compounds, flavonoids, organic acids, and volatile oils (Ibrahim and Alshammaa, 2023), in addition to the richness of its seeds in oil, which is considered one of the richest plant sources of  $\gamma$ -linolenic acid (GLA), a polyunsaturated fatty acid of high nutritional and pharmaceutical value (Latoch *et al.*, 2025). Borage oil is used in pharmaceutical industries, cosmetics, and dietary supplements due to its anti-inflammatory and antioxidant properties, its role in maintaining skin health, improving immune system function, and preventing certain chronic diseases - factors that have made it a promising medicinal crop of high economic value (Casas-Cardoso *et al.*, 2021 and Sytar *et al.*, 2021). Its fresh leaves and flowers are also used in some traditional food systems to add a distinctive flavor to salads and beverages, in addition to their use in folk medicine since ancient times. However, recent studies emphasize the necessity of safe use of plant parts according to health guidelines, since some parts of the plant contain varying amounts of pyrrolizidine alkaloids, which requires attention to the quality and source of the plant material when used for food or medicinal purposes (Latoch *et al.*, 2025 and Mehrabani *et al.*, 2020).

#### **Treatment with NPK 16-16-16 Fertilizer:**

NPK 16-16-16 fertilizer is one of the compound, balanced mineral fertilizers widely used in agricultural production due to its content of essential macronutrients. It consists of three essential macronutrients at an equal concentration of 16% each: the nitrogen fraction is supplied by nitrogen sources such as ammonium nitrate ( $\text{NH}_4\text{NO}_3$ ) and urea ( $\text{CO}(\text{NH}_2)_2$ ), while phosphorus is supplied from monoammonium phosphate (MAP) or diammonium phosphate (DAP), and potassium is supplied from potassium chloride (KCl) or potassium sulfate ( $\text{K}_2\text{SO}_4$ ). The fertilizer thus provides a balanced composition of nitrogen, phosphorus, and potassium at 16% N, 16% P, and 16% K, to support the plant's basic nutritional requirements during its different growth and development stages, which play complementary roles in regulating plant growth, development, and productivity.

Borage (*B. officinalis* L.) is highly dependent on the balanced availability of these elements, given its nutritional needs for producing biomass, flowers, and seeds rich in fixed oil, particularly  $\gamma$ -linolenic acid (GLA). Hawkesford *et al.* (2023) indicated that nitrogen, phosphorus, and potassium are essential elements that control many physiological and vital processes related to vegetative and root growth, dry matter formation, and yield. Nitrogen is considered the most influential element in vegetative growth, as it is incorporated into amino acids, proteins, nucleic acids, and chlorophyll, thereby enhancing cell division and elongation, increasing leaf area, chlorophyll content, photosynthetic efficiency, and the accumulation of carbohydrates and dry matter, and consequently supporting biomass formation and productivity, as noted by Fageria (2024).

Phosphorus plays a pivotal role in intracellular energy transfer through adenosine triphosphate (ATP) compounds, and is incorporated into nucleic acids and cell membranes, in addition to its role in stimulating root system growth and branching and improving the efficiency of water and nutrient absorption, alongside its contribution to flowering, fruit set, and seed formation and maturation (Lambers and Oliveira, 2019). Potassium, on the other hand, regulates water balance and osmotic pressure and controls stomatal opening and closing, thereby enhancing water-use efficiency and the plant's ability to tolerate drought and environmental stresses. It also activates numerous enzymes associated with photosynthesis, respiration, protein synthesis, and sugar transport (Wang and Wu, 2013). Potassium further contributes to the translocation of photosynthates from leaves to growing and storage organs, supports dry matter accumulation, and improves flower and seed traits and yield quality (Zörb *et al.*, 2014). Borage's specific response confirms the importance of balanced management of these elements, as Al-Mohammad *et al.* (2023) showed that increasing nitrogen fertilization levels improved vegetative growth and yield components, including number of flowers and seed yield, in addition to improving fixed oil content and some essential fatty acids, particularly  $\gamma$ -linolenic acid (GLA). Accordingly, the use of NPK 16-16-16 fertilizer provides a balanced source of macronutrients and can contribute to supporting vegetative and root growth, flowering, and seed formation, which is positively reflected in the quantity and quality of borage production.

## Treatment with Bio Health WSG

Bio Health WSG (Water-Soluble Granules) is an organic fertilizer and water-soluble biostimulant produced by Humintech GmbH. It consists (on a dry-matter basis) of an integrated set of organic and biological components, with a dry matter content of 83–85%. It contains total humic acids at 65–66%, fulvic acid at 2–3%, along with 10% seaweed extract (*Ascophyllum nodosum*). The product also contains potassium humate at 70–75% and potassium oxide ( $K_2O$ ) at 10–12%, while organic matter content reaches 65–69%. The biological component includes the fungus *Trichoderma harzianum* at a density of  $10^7$  CFU·g<sup>-1</sup>, the product's pH ranges between 9.5–10.5, and its bulk density is 0.55–0.65 g·cm<sup>-3</sup>.

This composition indicates that BioHealth® TH WSG combines humic, organic, and biological components, making it suitable for use as a biostimulant and growth-medium enhancer. It is used within plant nutrition and sustainable agriculture programs to improve root-zone characteristics and increase plant growth and productivity efficiency. Its effect depends on the integration of potassium humic acids, *Ascophyllum nodosum* seaweed extract, and beneficial microorganisms, particularly *Trichoderma harzianum* and *Bacillus amyloliquefaciens*, as these components work in an integrated manner to improve root system growth and branching, activate microbial activity in the rhizosphere, and enhance the efficiency of water and nutrient absorption, in addition to supporting the plant's ability to withstand unfavorable environmental conditions such as drought and salinity (**Humintech GmbH, 2025**).

Company data indicate that the compound contains approximately 10% seaweed extract, 70–75% humic acids, and 10–12%  $K_2O$  on a dry-matter basis, with a density of beneficial microorganisms ranging between  $10^6$ – $10^7$  colony-forming units per gram. It can be applied directly to the soil or added to the growing medium, and can also be used as a root-dipping solution before planting or within some hydroponic systems, with the aim of promoting root growth and biomass, improving nutrient-use efficiency, and supporting the productivity of medicinal and aromatic crops.

The importance of humic acids in this type of biostimulant lies in their ability to improve soil and root-zone properties and increase nutrient availability and uptake, while seaweed extracts contribute to stimulating several physiological processes related to growth, cell division, and photosynthetic efficiency, and beneficial microorganisms help improve the microbial environment around the roots and promote their growth. **Rouphael and Colla (2020)** showed that the integration of humates, seaweed extracts, and beneficial microorganisms can improve plant growth, productivity, and nutrient-use efficiency, in addition to enhancing plants' ability to adapt to environmental stresses. **Alharbi et al. (2022)** also indicated that combining potassium humate with the fungus *Trichoderma harzianum* improved root system growth, photosynthetic efficiency, and nutrient absorption, while reducing oxidative damage in plants exposed to saline and drought conditions. Similarly, **Ekin et al. (2020)** showed that the integration of humic acid with strains of *Bacillus subtilis* in safflower (*Carthamus tinctorius*) improved nutrient absorption, which was reflected in increased seed and oil production, confirming the importance of the interaction between humic substances and microorganisms in improving nutrition efficiency and plant production.

*Trichoderma* fungi also represent an important component in biostimulant programs due to their ability to improve root growth and enhance nutrient absorption efficiency, in addition to their role in reducing the effect of certain plant pathogens. A study by **Andrzejak et al. (2021)**, conducted on basil (*Ocimum basilicum*), showed that the use of *Trichoderma asperellum* contributed to reducing the severity of foliar diseases and improving plant growth, supporting the potential use of *Trichoderma* fungi in more sustainable production systems for medicinal and aromatic plants. These findings are consistent with the modern trend toward using biostimulants as a means of raising the efficiency of agricultural input use and reducing excessive dependence on chemical fertilizers, as **Sun et al. (2024)** indicated that biofertilizers and bio-enhancers represent one of the promising options for achieving sustainable agriculture by supporting crop productivity, improving resource-use efficiency, and reducing the environmental impacts associated with intensive use of mineral fertilizers.

Studies that used components similar to those of Bio Health WSG have supported the positive response of medicinal and aromatic plants to these substances. A study by **Alhasan et al. (2023)** on

borage (*Borago officinalis* L.) showed that using compound NPK fertilizer at concentrations of 0 and 2 g·L<sup>-1</sup>, along with seaweed extract at concentrations of 0 and 2 g·L<sup>-1</sup>, led to a clear improvement in vegetative growth traits, chlorophyll content, and seed production, with the 2 g·L<sup>-1</sup> concentration of seaweed extract being the most effective. These results indicate the importance of components extracted from seaweed in improving the efficiency of the plant's physiological processes, particularly when combined with mineral nutrition.

In another study, **El-Nakhel et al. (2023)** showed that using *Ascophyllum nodosum* seaweed extract at concentrations of 1.5 and 3 g·L<sup>-1</sup> in lettuce (*Lactuca sativa* L.) led to a significant improvement in vegetative growth traits and chlorophyll indicators compared to the control treatment, with the 3 g·L<sup>-1</sup> concentration being more efficient, as plants treated with it recorded the highest values for the leaf chlorophyll index (SPAD) and total chlorophyll content, along with a significant increase in fresh biomass and improved vegetative growth. This improvement was attributed to the ability of seaweed extract to activate physiological processes, raise photosynthetic efficiency, and improve nutrient absorption, which was reflected in increased growth and biological production. These results support the importance of *Ascophyllum nodosum* extract as one of the active components in compound biostimulants, including Bio Health WSG, particularly when used within integrated nutrition programs.

In general, the combination of humic acids, *Ascophyllum nodosum* extract, and beneficial microorganisms in Bio Health WSG provides integrated mechanisms for improving the root environment, raising the efficiency of water and nutrient uptake, activating physiological processes, and enhancing growth and tolerance to environmental stresses. Its use together with mineral fertilization and amino acids can therefore represent an integrative approach to improving vegetative and root growth, flowering, and productivity in borage, while potentially contributing to reducing dependence on chemical inputs and achieving more efficient and sustainable management.

### Amino Acids

Amino acids are foliar-applied biostimulants composed of a group of nutritional and organic components of plant origin. The total amino acid content is 18.5%, while free amino acids constitute 8.2%, the form most readily available for plant uptake. The compound also contains 40.0% organic matter, 3.0% organic nitrogen, and 3.0% total nitrogen (N), in addition to 3.0% potassium oxide (K<sub>2</sub>O), with a pH of 5.6. It aims to improve plant growth by enhancing chlorophyll synthesis, improving photosynthetic efficiency, and increasing the capacity of antioxidant systems, as it provides the plant with the basic building blocks for proteins and enzymes, in addition to its role in enhancing nutrient absorption, stimulating antioxidant formation, and helping resist stresses such as drought or salinity (**Henderson et al., 2025**).

**Hala (2024)** indicated that foliar spraying of *B. officinalis* with amino acid solutions at concentrations ranging between 0.5-1.5g·L<sup>-1</sup> improved vegetative growth and significantly increased plant height and the number of branches and leaves, in addition to stimulating flower formation compared to the control treatment. This was attributed to their role in activating vital enzymes and increasing photosynthetic and nitrogen-use efficiency, which was positively reflected in growth and flowering.

**Ibrahim et al. (2025)** reported that using biostimulants rich in amino acids and vitamins on borage improved growth traits, increased biomass, and raised flower and seed oil production, as amino acids contributed to raising nutrient absorption and activating the physiological processes responsible for flowering.

The study aimed to evaluate the effect of NPK fertilizer levels on vegetative growth, flowering, and flower productivity of *B. officinalis* L., and to determine the efficiency of Bio-Health WSG and amino acids in promoting growth, improving physiological status, and nutrient absorption efficiency, as well as to evaluate the effect of the interaction among these treatments and identify the most efficient combination for improving plant productivity and quality under the conditions of Nineveh Governorate, thereby supporting the adoption of more efficient and sustainable agricultural practices.

## 2. Materials and Methods

This study was conducted to evaluate the effect of mineral fertilization with NPK (16-16-16) at three levels (0, 100, and 150 kg·ha<sup>-1</sup>), biofertilization with Bio Health WSG at two concentrations (0 and 3 kg·ha<sup>-1</sup>), and foliar spraying with amino acids at three concentrations (0, 1.5, and 2.5 ml·L<sup>-1</sup>), as well as the interactions among them, on the vegetative and floral growth and yield of the bee-bread plant (borage) (*B. officinalis* L.), in order to determine the best fertilization combination for improving the vegetative growth, flowering, and yield traits of this plant under the environmental conditions of Mosul city.

Source of seeds used: The borage (*B. officinalis* L.) seeds used in this study were obtained from a reliable commercial agricultural source (Alam Al-Zira'a, Iraq). These are cultivated seeds whose genetic identity had been previously verified using polymerase chain reaction (PCR) technique and ITS region analysis, where the molecular diagnostic results showed a high match (98.74%) with the reference sequence in the international gene bank (NCBI), with no gaps in alignment. The sequence was deposited under accession number (PV848435.1) in comparison with the reference (MT476300.1), confirming the accuracy of the genetic identity and reliability of the plant material used in the study (Abdullah, 2026).

Field soil analysis: Soil samples were collected and analyzed in the Central Laboratory of the College of Agriculture and Forestry, University of Mosul, and their specifications are shown in Table (1).

**Table (1). Some physical and chemical properties of the soil used before planting for the year (2024–2025) in the experiment\***

| Measurement         |      | Result |            |
|---------------------|------|--------|------------|
| N%                  |      | 0.097  |            |
| P ppm               |      | 8.48   |            |
| K ppm               |      | 313    |            |
| pH                  |      | 8.2    |            |
| Ec                  |      | 0.93   |            |
| CaCO <sub>3</sub> % |      | 26.4   |            |
| Organic matter %    |      | 1.58   |            |
| Soil separates      |      |        |            |
| Soil model          | Sand | 67.05  | Sandy loam |
|                     | Clay | 17.95  |            |
|                     | Silt | 15     |            |

• Analysis was conducted in the Central Laboratory of the College of Agriculture and Forestry, University of Mosul.

The experiment was designed as a factorial experiment in a split-split plot arrangement within a Randomized Complete Block Design (RCBD), with three factors, three replicates, and ten plants per replicate. The results were statistically analyzed using the **SAS system (2017)**, and means were compared using Duncan's Multiple Range Test at a probability level of 0.05 (**Al-Rawi and Khalaf Allah, 2000**). Accordingly, the study included 18 factorial treatments: three concentrations of NPK 16-16-16, two concentrations of Bio Health WSG, and three concentrations of amino acid extract, i.e., the experiment comprised a (3×2×3) factorial arrangement, with each treatment replicated three times.

First factor: Three levels of NPK 16-16-16 fertilizer, considered the main factor and placed in the main plots. It is a balanced, triple-element compound fertilizer with the chemical formula (N+P<sub>2</sub>O<sub>5</sub>+K<sub>2</sub>O<sub>5</sub>), added to the soil in two equal split applications; the first application was carried out when plants reached a height of 15–20 cm, while the second application was made 30 days after the first.

Second factor: Represented by fertilization with Bio Health WSG at two concentrations (0 and 3 kg·ha<sup>-1</sup>). The biostimulant was applied to the soil in two split applications; the first coincided with one week after the first NPK application, while the second was applied 30 days after the first, with the aim of promoting root growth and increasing nutrient-absorption efficiency during the different growth stages. Control plants were treated with distilled water only. This factor was considered a sub-factor within the experimental design.

Third factor: Represented by treatment with the commercial preparation PIXAN AMINO PLANTA, an amino acid-based plant biostimulant. This factor was considered a sub-sub-factor within the experimental design. It was used at three concentrations (0, 1.5, and 2.5 ml·L<sup>-1</sup>) and applied as a foliar spray three times during the growing season. The first spray was applied 10 days after the first application of the BioHealth® TH BS WSG biostimulant, and the second and third sprays were applied at 15-day intervals, while control plants were sprayed with distilled water only.

### Studied Traits

Plant height (cm): Measured using a measuring tape from the soil surface to the tip of the plant's branches.

Stem diameter (mm): Measured using a caliper.

Number of branches (branch·plant<sup>-1</sup>): Determined by counting the main branches of the plant.

Leaf area (cm<sup>2</sup>·plant<sup>-1</sup>): Determined according to the method of **Scott (1973)**, by calculating the ratio of the dry weight of leaf discs of known area to the total dry weight of the plant's leaves, according to the equation of **Roy (1981)**:

$$\text{Leaf Area (cm}^2\text{·plant}^{-1}\text{)} = [\text{Disc Area (cm}^2\text{)} \times (\text{Dry Weight of Discs (g)} + \text{Total Dry Weight of Plant Leaves (g)})] \div \text{Dry Weight of Discs (g)}$$

Number of leaves (leaf·plant<sup>-1</sup>).

Number of flowers (flower·plant<sup>-1</sup>).

Total yield (kg·ha<sup>-1</sup>): Calculated based on a planted area of the dunam equal to 2200 m<sup>2</sup>, according to the following equation:

$$\text{Total Yield (kg·ha}^{-1}\text{)} = [\text{Experimental Unit Yield (kg)} \times 2200 \times 4] \div \text{Experimental Unit Area (m}^2\text{)}$$

## 3. Results and Discussion

### Plant Height (cm)

It is evident from the data in Table (2) that there was a significant increase in plant height as a result of mineral (NPK) fertilization, as the 100 kg·ha<sup>-1</sup> level achieved the highest average plant height of 96.46 cm, significantly outperforming the other fertilization levels, while the control treatment (0 kg·ha<sup>-1</sup>) recorded the lowest average of 74.33 cm. Fertilization with Bio Health WSG at 3 kg·ha<sup>-1</sup> also led to a significant increase in plant height, with an average of 84.44 cm, compared to the control treatment, which recorded the lowest significant value of 81.85 cm. In contrast, no significant differences were observed among the different amino acid concentrations.

The binary interaction data between mineral (NPK) fertilizer and Bio Health WSG show significant differences, with the best value recorded for NPK at 100 kg·ha<sup>-1</sup> combined with 3 kg·ha<sup>-1</sup> Bio Health WSG, reaching 98.88 cm, compared to the lowest value for the control treatment at 68.97 cm. The binary interaction between mineral (NPK) fertilizer and amino acids also showed significant differences among the different treatments, with the best values recorded when NPK at the 100 kg level was combined with any amino acid concentration (0, 1.5, and 2.5 ml·L<sup>-1</sup>), reaching 94.63, 98.17, and 96.58 cm, respectively. In contrast, the control treatment recorded the lowest significant value of 71.09 cm. The interaction between Bio Health WSG and amino acids showed significant differences among some treatments, as the treatment of 3 kg·ha<sup>-1</sup> Bio Health WSG combined with (1.5 and 2.5) ml·L<sup>-1</sup> amino acids recorded the highest significant values of (85.43 and 85.20) cm, respectively, compared to the lowest significant value of the control treatment at 81.08 cm.

Regarding the triple interaction between mineral (NPK) fertilizer, Bio Health WSG, and amino acids, the results showed significant differences among the interaction treatments, with the treatment of 100 kg·ha<sup>-1</sup> NPK combined with Bio Health WSG and 2.5 ml·L<sup>-1</sup> amino acids recording the highest significant value of 102.63 cm, compared to the lowest significant value recorded for the control treatment at 65.97 cm.

**Table (2). Effect of NPK fertilizer, Bio Health extract, and amino acid extract on plant height (cm) of borage (*B. officinalis* L.)**

| NPK Fertilizer<br>kg ha <sup>-1</sup> | Bio Health<br>kg ha <sup>-1</sup> | Amino acid ml L <sup>-1</sup> |           |           | Fertilizer<br>+ Bio<br>Health | Effect of<br>NPK<br>Fertilizer | Effect of<br>Bio<br>Health |
|---------------------------------------|-----------------------------------|-------------------------------|-----------|-----------|-------------------------------|--------------------------------|----------------------------|
|                                       |                                   | 0                             | 1.5       | 2.5       |                               |                                |                            |
| 0                                     | 0                                 | 65.97 h                       | 69.12 gh  | 71.70 fg  | 68.93 e                       |                                |                            |
|                                       | 3                                 | 76.22 ef                      | 78.13 de  | 84.83 c   | 79.73 c                       |                                |                            |
| 100                                   | 0                                 | 92.27 b                       | 93.71 b   | 96.17 b   | 94.05 b                       |                                |                            |
|                                       | 3                                 | 97.00 ab                      | 102.63 a  | 97.00 ab  | 98.88 a                       |                                |                            |
| 150                                   | 0                                 | 85.00 c                       | 82.90 cd  | 79.80 c-e | 82.57 c                       |                                |                            |
|                                       | 3                                 | 74.83 e-g                     | 74.83 e-g | 74.47 e-g | 74.71 d                       |                                |                            |
| NPK Fertilizer<br>+ Amino acid        | 0                                 | 71.09 d                       | 73.63 cd  | 78.27 b   |                               | 74.33 c                        |                            |
|                                       | 100                               | 94.63 a                       | 98.17 a   | 96.58 a   |                               | 96.46 a                        |                            |
|                                       | 150                               | 79.92 b                       | 78.87 b   | 77.13 bc  |                               | 78.64 b                        |                            |
| Bio Health +<br>Amino acid            | 0                                 | 81.08 c                       | 81.91 bc  | 82.56 a-c |                               |                                | 81.85 b                    |
|                                       | 3                                 | 82.68 a-c                     | 85.20 a   | 85.43 a   |                               |                                | 84.44 a                    |
| Effect of Amino acid                  |                                   | 81.88 a                       | 83.55 a   | 83.99 a   |                               |                                |                            |

• Treatments sharing the same letter do not differ significantly from each other at the 5% probability level.

### Number of Branches (branch·plant<sup>-1</sup>)

The data in Table (3) show a significant increase in the number of branches as a result of mineral (NPK) fertilization, with the 100 kg·ha<sup>-1</sup> level achieving the highest significant value of 21.68 branch·plant<sup>-1</sup>, outperforming the control treatment, which recorded 15.03 branch·plant<sup>-1</sup>. Fertilization with Bio Health WSG at 3 g·L<sup>-1</sup> also resulted in the best significant value of 20.27 branch·plant<sup>-1</sup>, compared to the lowest value of 8.33 branch·plant<sup>-1</sup> for the control treatment. Amino acids, however, showed no significant effect on this trait.

The binary interaction between mineral (NPK) fertilizer and Bio Health WSG showed significant differences among treatments, with the treatment of 100 kg·ha<sup>-1</sup> combined with 3 kg·ha<sup>-1</sup> Bio Health WSG recording the highest significant value of 24.56 branch·plant<sup>-1</sup>, while the control treatment recorded the lowest significant value of 12.31 branch·plant<sup>-1</sup>. The binary interaction between mineral (NPK) fertilizer and amino acids also showed significant differences among treatments, with the treatment of 100 kg·ha<sup>-1</sup> combined with 2.5 ml·L<sup>-1</sup> recording the highest average of 24.00 branch·plant<sup>-1</sup>, while the control treatment recorded the lowest value of 14.12 branch·plant<sup>-1</sup>. The binary interaction between Bio Health WSG and amino acids showed significant differences among treatments, with the treatment of 3 kg·ha<sup>-1</sup> Bio Health WSG combined with 2.5 ml·L<sup>-1</sup> amino acids recording the highest average of 20.96 branch·plant<sup>-1</sup>, while the treatment without Bio Health WSG or amino acids recorded the lowest significant value of 17.67 branch·plant<sup>-1</sup>.

Regarding the triple interaction between mineral (NPK) fertilizer, Bio Health WSG, and amino acids, the results showed significant differences among the interaction treatments, with the treatment of 100 kg·ha<sup>-1</sup> NPK combined with 3 kg·ha<sup>-1</sup> Bio Health WSG combined with 1.5 ml·L<sup>-1</sup> amino acids recording the highest average of 27.17 branch·plant<sup>-1</sup>, while the control treatment recorded the lowest significant value of 12.31 branch·plant<sup>-1</sup>.

The increase observed in the number of branches is consistent with amino acids acting as complementary metabolic stimulants rather than substitutes for macronutrients in determining the branching pattern (Rouphael and Colla, 2020).

**Table (3). Effect of NPK fertilizer, Bio Health extract, and amino acid extract on number of branches (branch·plant<sup>-1</sup>) of borage (*B. officinalis* L.)**

| NPK Fertilizer<br>kg ha <sup>-1</sup> | Bio Health<br>kg ha <sup>-1</sup> | Amino acid ml L <sup>-1</sup> |           |           | Fertilizer<br>+ Bio<br>Health | Effect of<br>NPK<br>Fertilizer | Effect of<br>Bio<br>Health |
|---------------------------------------|-----------------------------------|-------------------------------|-----------|-----------|-------------------------------|--------------------------------|----------------------------|
|                                       |                                   | 0                             | 1.5       | 2.5       |                               |                                |                            |
| 0                                     | 0                                 | 12.31 g                       | 13.55 fg  | 15.87 e-g | 13.91 e                       |                                |                            |
|                                       | 3                                 | 15.93 e-g                     | 16.20 e-g | 16.30 e-g | 16.14 de                      |                                |                            |
| 100                                   | 0                                 | 17.50 d-f                     | 18.10 d-f | 20.83 b-e | 18.81 cd                      |                                |                            |
|                                       | 3                                 | 21.97 b-d                     | 24.53 ab  | 27.17 a   | 24.56 a                       |                                |                            |
| 150                                   | 0                                 | 23.20 a-c                     | 22.18 b-d | 21.40 b-d | 22.26 ab                      |                                |                            |
|                                       | 3                                 | 20.53 b-e                     | 20.40 b-e | 19.40 c-e | 20.11 bc                      |                                |                            |
| NPK Fertilizer<br>+ Amino acid        | 0                                 | 14.12 c                       | 14.88 c   | 16.08 c   |                               | 15.03 b                        |                            |
|                                       | 100                               | 19.73 b                       | 21.32 ab  | 24.00 a   |                               | 21.68 a                        |                            |
|                                       | 150                               | 21.87 ab                      | 21.29 ab  | 20.40 b   |                               | 21.19 a                        |                            |
| Bio Health +<br>Amino acid            | 0                                 | 17.67 b                       | 17.94 b   | 19.37 ab  |                               |                                | 18.33 b                    |
|                                       | 3                                 | 19.48 ab                      | 20.38 ab  | 20.96 a   |                               |                                | 20.27 a                    |
| Effect of Amino acid                  |                                   | 18.57 a                       | 19.16 a   | 20.16 a   |                               |                                |                            |

• Treatments sharing the same letter do not differ significantly from each other at the 5% probability level.

### Stem Diameter (mm)

The data in Table (4) show that fertilization with NPK led to a significant increase in stem diameter, with the 150 kg·ha<sup>-1</sup> level recording the highest significant value of 11.29 mm, followed by the 100 kg·ha<sup>-1</sup> level at 10.04 mm, while the control treatment recorded the lowest significant value of 7.36 mm. Fertilization with the Bio Health preparation also caused a significant increase in this trait, with the highest significant value of 10.14 mm at the 3 g·L<sup>-1</sup> concentration, compared to 8.98 mm without addition. For amino acid treatment, the 2.5 ml·L<sup>-1</sup> concentration achieved the highest significant value of 9.73 mm, not significantly different from the 1.5 ml·L<sup>-1</sup> concentration, which recorded 9.68 mm, while the treatment without addition recorded the lowest significant value of 9.28 mm.

The binary interaction data between NPK and Bio Health showed significant differences among treatments, with plants treated with 100 kg·ha<sup>-1</sup> NPK combined with 3 kg·ha<sup>-1</sup> Bio Health recording the highest significant value of 11.76 mm, not significantly different from the treatment of 150 kg·ha<sup>-1</sup> without Bio Health, which reached 11.72 mm, while the lowest significant value was recorded for the control treatment at 6.90 mm. The interaction between NPK and amino acids showed the best significant value at the 150 kg·ha<sup>-1</sup> NPK level without amino acid spraying, reaching 11.55 mm, while the control treatment recorded the lowest significant value of 7.03 mm. The binary interaction between Bio Health and amino acids also showed significant differences, with the treatment of Bio Health at 3 kg·ha<sup>-1</sup> combined with either (1.5 or 2.5) ml·L<sup>-1</sup> amino acids achieving the highest significant values of (10.24 and 10.41) mm, respectively, while the control treatment recorded the lowest significant value of 8.78 mm.

The triple interaction data between NPK, Bio Health, and amino acids showed significant differences among treatments, with the highest significant value of 12.47 mm recorded for the treatment combining 150 kg·ha<sup>-1</sup> NPK, 3 kg·ha<sup>-1</sup> Bio Health, and 2.5 ml·L<sup>-1</sup> amino acids, while the lowest significant value of 6.43 mm was recorded for the control treatment. This indicates that the integration of mineral fertilization, biostimulant, and amino acids contributed to achieving the best response for the studied trait compared to the control treatment.

**Table (4). Effect of NPK fertilizer, Bio Health extract, and amino acid extract on stem diameter (mm) of borage (*B. officinalis* L.)**

| NPK Fertilizer<br>kg ha <sup>-1</sup> | Bio Health<br>kg ha <sup>-1</sup> | Amino acid ml L <sup>-1</sup> |           |          | Fertilizer<br>+ Bio<br>Health | Effect of<br>NPK<br>Fertilizer | Effect of<br>Bio<br>Health |
|---------------------------------------|-----------------------------------|-------------------------------|-----------|----------|-------------------------------|--------------------------------|----------------------------|
|                                       |                                   | 0                             | 1.5       | 2.5      |                               |                                |                            |
| 0                                     | 0                                 | 6.43 k                        | 6.90 jk   | 7.37 ij  | 6.90 e                        |                                |                            |
|                                       | 3                                 | 7.63 hi                       | 7.90 hi   | 7.90 hi  | 7.81 d                        |                                |                            |
| 100                                   | 0                                 | 7.97 hi                       | 8.23 gh   | 8.77 g   | 8.32 c                        |                                |                            |
|                                       | 3                                 | 10.53 ef                      | 12.72 ab  | 12.47 a  | 11.76 a                       |                                |                            |
| 150                                   | 0                                 | 11.93 a-c                     | 11.70 b-d | 11.53 cd | 11.72 a                       |                                |                            |
|                                       | 3                                 | 11.17 de                      | 11.07 d-f | 10.73 f  | 10.87 b                       |                                |                            |
| NPK Fertilizer<br>+ Amino acid        | 0                                 | 7.03 g                        | 7.40 fg   | 7.63 f   |                               | 7.36 c                         |                            |
|                                       | 100                               | 9.25 e                        | 10.25 d   | 10.62 cd |                               | 10.04 b                        |                            |
|                                       | 150                               | 11.55 a                       | 11.38 ab  | 10.95 bc |                               | 11.29 a                        |                            |
| Bio Health +<br>Amino acid            | 0                                 | 8.78 d                        | 8.94 cd   | 9.22 c   |                               |                                | 8.98 b                     |
|                                       | 3                                 | 9.78 b                        | 10.41 a   | 10.24 a  |                               |                                | 10.14 a                    |
| Effect of Amino acid                  |                                   | 9.28 b                        | 9.68 a    | 9.73 a   |                               |                                |                            |

• Treatments sharing the same letter do not differ significantly from each other at the 5% probability level.

### Leaf Area (cm<sup>2</sup>·plant<sup>-1</sup>)

The data in Table (5) show that NPK fertilization caused significant differences in leaf area of borage, with the 100 kg·ha<sup>-1</sup> level recording the highest significant value of 608.94 cm<sup>2</sup>·plant<sup>-1</sup>, while the control treatment recorded the lowest significant value of 382.16 cm<sup>2</sup>·plant<sup>-1</sup>. Fertilization with Bio Health extract also caused a significant increase in leaf area, with the highest significant value of 518.40 cm<sup>2</sup>·plant<sup>-1</sup> at the 3 kg·ha<sup>-1</sup> concentration, compared to 426.56 cm<sup>2</sup>·plant<sup>-1</sup> without fertilization. Amino acid treatment at concentrations of (1.5 and 2.5) ml·L<sup>-1</sup> achieved the highest significant values of (477.19 and 492.73) cm<sup>2</sup>·plant<sup>-1</sup>, respectively, while the treatment without addition recorded the lowest significant value of 447.52 cm<sup>2</sup>·plant<sup>-1</sup>.

The binary interaction between NPK and Bio Health showed significant differences among treatments, with plants treated with 100 kg·ha<sup>-1</sup> NPK combined with 3 kg·ha<sup>-1</sup> Bio Health recording the highest significant value of 704.98 cm<sup>2</sup>·plant<sup>-1</sup>, while the untreated control recorded the lowest significant value of 341.19 cm<sup>2</sup>·plant<sup>-1</sup>. The binary interaction between NPK and amino acids also showed significant differences, with plants treated with 100 kg·ha<sup>-1</sup> NPK combined with 1.5 and 2.5 ml·L<sup>-1</sup> amino acids recording the highest significant values of (622.98 and 646.53) cm<sup>2</sup>·plant<sup>-1</sup>, respectively, while the treatment without either NPK or amino acids recorded the lowest significant value of 365.54 cm<sup>2</sup>·plant<sup>-1</sup>. The binary interaction between Bio Health extract and amino acids also showed significant differences, with plants treated with 3 kg·ha<sup>-1</sup> Bio Health combined with (1.5 and 2.5) ml·L<sup>-1</sup> amino acids recording the highest significant values of (535.67 and 540.90) cm<sup>2</sup>·plant<sup>-1</sup>, respectively, while the treatment without Bio Health or amino acids recorded the lowest significant value of 416.40 cm<sup>2</sup>·plant<sup>-1</sup>.

In general, the triple interaction data between NPK, Bio Health extract, and amino acids showed significant differences among treatments, with plants treated with 100 kg·ha<sup>-1</sup> NPK combined with 3 kg·ha<sup>-1</sup> Bio Health extract and 2.5 ml·L<sup>-1</sup> amino acids recording the highest significant value of 743.88 cm<sup>2</sup>·plant<sup>-1</sup>, not significantly different from the same treatment at 1.5 ml·L<sup>-1</sup> amino acids, which reached 732.22 cm<sup>2</sup>·plant<sup>-1</sup>, while the control treatment (without NPK, Bio Health, or amino acids) recorded the lowest significant value of 315.11 cm<sup>2</sup>·plant<sup>-1</sup>, indicating that the integration of mineral fertilization, biostimulant, and amino acids contributed to achieving the best leaf area response in borage.

**Table (5). Effect of NPK fertilizer, Bio Health extract, and amino acid extract on leaf area ( $\text{cm}^2 \cdot \text{plant}^{-1}$ ) of borage (*B. officinalis* L.)**

| NPK Fertilizer<br>$\text{kg ha}^{-1}$ | Bio Health<br>$\text{kg ha}^{-1}$ | Amino acid $\text{ml L}^{-1}$ |           |           | Fertilizer<br>+ Bio<br>Health | Effect of<br>NPK<br>Fertilizer | Effect of<br>Bio<br>Health |
|---------------------------------------|-----------------------------------|-------------------------------|-----------|-----------|-------------------------------|--------------------------------|----------------------------|
|                                       |                                   | 0                             | 1.5       | 2.5       |                               |                                |                            |
| 0                                     | 0                                 | 340.94 ij                     | 315.11 j  | 367.51 hi | 341.19 d                      |                                |                            |
|                                       | 3                                 | 395.08 gh                     | 415.97 fg | 458.32 ef | 423.13 c                      |                                |                            |
| 100                                   | 0                                 | 475.79 de                     | 513.73 cd | 549.18 c  | 512.90 b                      |                                |                            |
|                                       | 3                                 | 638.84 b                      | 732.22 a  | 743.88 a  | 704.98 a                      |                                |                            |
| 150                                   | 0                                 | 432.48 e-g                    | 427.30 fg | 417.00 fg | 425.59 c                      |                                |                            |
|                                       | 3                                 | 402.00 gh                     | 458.82 ef | 420.49 gf | 427.10 c                      |                                |                            |
| NPK Fertilizer<br>+ Amino acid        | 0                                 | 368.01 d                      | 365.54 d  | 412.92 c  |                               | 382.16 c                       |                            |
|                                       | 100                               | 557.31 b                      | 622.98 a  | 646.53 a  |                               | 608.94 a                       |                            |
|                                       | 150                               | 417.24 c                      | 443.06 c  | 418.74 c  |                               | 426.35 b                       |                            |
| Bio Health +<br>Amino acid            | 0                                 | 416.40 d                      | 418.72 d  | 444.56 c  |                               |                                | 426.56 b                   |
|                                       | 3                                 | 478.64 b                      | 535.67 a  | 540.90 a  |                               |                                | 518.40 a                   |
| Effect of Amino acid                  |                                   | 447.52 b                      | 477.19 a  | 492.73 a  |                               |                                |                            |

• Treatments sharing the same letter do not differ significantly from each other at the 5% probability level.

### Number of Leaves ( $\text{leaf} \cdot \text{plant}^{-1}$ )

It is clearly evident from the data in Table (6) that NPK fertilization led to a significant increase in the number of leaves, with the two levels (100 and 150)  $\text{kg} \cdot \text{ha}^{-1}$  recording the two highest significant values of (89.00 and 87.94)  $\text{leaf} \cdot \text{plant}^{-1}$ , while the control treatment recorded the lowest significant value of 72.00  $\text{leaf} \cdot \text{plant}^{-1}$ . Fertilization with Bio Health extract also led to a significant increase in the number of leaves, with the highest significant value of 85.26  $\text{leaf} \cdot \text{plant}^{-1}$  at the 3  $\text{g} \cdot \text{L}^{-1}$  concentration, compared to 80.70  $\text{leaf} \cdot \text{plant}^{-1}$  without fertilization. For amino acid treatment, the 2.5  $\text{ml} \cdot \text{L}^{-1}$  concentration achieved the highest significant value of 84.33  $\text{leaf} \cdot \text{plant}^{-1}$ , while the treatment without addition recorded the lowest significant value of 81.78  $\text{leaf} \cdot \text{plant}^{-1}$ .

**Table (6). Effect of NPK fertilizer, Bio Health extract, and amino acid extract on number of leaves ( $\text{leaf} \cdot \text{plant}^{-1}$ ) of borage (*B. officinalis* L.)**

| NPK Fertilizer<br>$\text{kg ha}^{-1}$ | Bio Health<br>$\text{kg ha}^{-1}$ | Amino acid $\text{ml L}^{-1}$ |          |         | Fertilizer<br>+ Bio<br>Health | Effect of<br>NPK<br>Fertilizer | Effect of<br>Bio<br>Health |
|---------------------------------------|-----------------------------------|-------------------------------|----------|---------|-------------------------------|--------------------------------|----------------------------|
|                                       |                                   | 0                             | 1.5      | 2.5     |                               |                                |                            |
| 0                                     | 0                                 | 61.33 i                       | 65.33 h  | 73.00 g | 66.56 e                       |                                |                            |
|                                       | 3                                 | 75.33 g                       | 78.00 f  | 79.00 f | 77.44 d                       |                                |                            |
| 100                                   | 0                                 | 81.67 e                       | 84.33 e  | 87.00 d | 84.33 c                       |                                |                            |
|                                       | 3                                 | 91.00 c                       | 94.33 a  | 95.67 a | 93.67 a                       |                                |                            |
| 150                                   | 0                                 | 93.67 ab                      | 91.67 bc | 88.33 d | 91.22 b                       |                                |                            |
|                                       | 3                                 | 87.67 d                       | 83.33 e  | 83.00 e | 84.67 c                       |                                |                            |
| NPK Fertilizer<br>+ Amino acid        | 0                                 | 68.33 f                       | 71.67 e  | 76.00 d |                               | 72.00 b                        |                            |
|                                       | 100                               | 86.33 c                       | 89.33 b  | 91.33 a |                               | 89.00 a                        |                            |
|                                       | 150                               | 90.67 ab                      | 87.50 c  | 85.67 c |                               | 87.94 a                        |                            |
| Bio Health +<br>Amino acid            | 0                                 | 78.89 d                       | 80.44 c  | 82.78 b |                               |                                | 80.70 b                    |
|                                       | 3                                 | 84.67 a                       | 85.22 a  | 85.89 a |                               |                                | 85.26 a                    |
| Effect of Amino acid                  |                                   | 81.78 c                       | 82.83 b  | 84.33 a |                               |                                |                            |

• Treatments sharing the same letter do not differ significantly from each other at the 5% probability level.

The binary interaction between NPK and Bio Health showed significant differences among treatments, with plants treated with 100 kg·ha<sup>-1</sup> NPK combined with 3 kg·ha<sup>-1</sup> Bio Health recording the highest significant value of 93.67 leaf·plant<sup>-1</sup>, while the control treatment recorded the lowest significant value of 66.56 leaf·plant<sup>-1</sup>. The binary interaction between NPK and amino acids also showed significant differences, with plants treated with 100 kg·ha<sup>-1</sup> NPK combined with 2.5 ml·L<sup>-1</sup> amino acids recording the highest significant value of 91.33 leaf·plant<sup>-1</sup>, while the control treatment recorded the lowest significant value of 68.33 leaf·plant<sup>-1</sup>. For the binary interaction between Bio Health and amino acids, plants treated with 3 kg·ha<sup>-1</sup> Bio Health combined with any amino acid concentration recorded the highest significant values of (84.67, 85.22, and 85.89) leaf·plant<sup>-1</sup>, respectively, while the treatment without Bio Health or amino acids recorded the lowest significant value of 78.89 leaf·plant<sup>-1</sup>.

In general, the triple interaction data between NPK, Bio Health extract, and amino acids showed significant differences among treatments, with plants treated with 100 kg·ha<sup>-1</sup> NPK combined with 3 kg·ha<sup>-1</sup> Bio Health and amino acids at (1.5 and 2.5) ml·L<sup>-1</sup> recording the highest significant values of (94.33 and 95.67) leaf·plant<sup>-1</sup>, while the control treatment recorded the lowest significant value of 61.33 leaf·plant<sup>-1</sup>.

### Number of Flowers (flower·plant<sup>-1</sup>)

The data in Table (7) show significant differences in the number of flowers of borage (*B. officinalis* L.) as a result of the studied treatments. NPK fertilization at 100 kg·ha<sup>-1</sup> achieved the highest significant value of 3026.11 flower·plant<sup>-1</sup>, compared to the unfertilized treatment, which recorded 1267.56 flower·plant<sup>-1</sup>. Regarding the effect of Bio Health extract, its use at 3 kg·ha<sup>-1</sup> resulted in a significant increase in the number of flowers, reaching the highest significant value of 2448.59 flower·plant<sup>-1</sup>, compared to 1811.19 flower·plant<sup>-1</sup> without addition. Amino acid extract results showed that spraying at 2.5 ml·L<sup>-1</sup> gave the highest significant value of 2204.78 flower·plant<sup>-1</sup>, not significantly different from the 1.5 ml·L<sup>-1</sup> concentration, which reached 2189.17 flower·plant<sup>-1</sup>, while the control treatment recorded the lowest value of 1995.72 flower·plant<sup>-1</sup>.

**Table (7). Effect of NPK fertilizer, Bio Health extract, and amino acid extract on number of flowers (flower·plant<sup>-1</sup>) of borage (*B. officinalis* L.)**

| NPK Fertilizer kg ha <sup>-1</sup> | Bio Health kg ha <sup>-1</sup> | Amino acid ml L <sup>-1</sup> |             |             | Fertilizer + Bio Health | Effect of NPK Fertilizer | Effect of Bio Health |
|------------------------------------|--------------------------------|-------------------------------|-------------|-------------|-------------------------|--------------------------|----------------------|
|                                    |                                | 0                             | 1.5         | 2.5         |                         |                          |                      |
| 0                                  | 0                              | 908.67 h                      | 914.33 h    | 1289.33 gh  | 1037.44 e               |                          |                      |
|                                    | 3                              | 1440.67 fg                    | 1489.67 fg  | 1562.67 eg  | 1497.67 d               |                          |                      |
| 100                                | 0                              | 1587.33 ef                    | 2105.33 cd  | 2274.67 cd  | 1989.11 c               |                          |                      |
|                                    | 3                              | 3497.67 b                     | 4312.00 a   | 4379.67 a   | 4063.11 a               |                          |                      |
| 150                                | 0                              | 2553.67 c                     | 2470.33 c   | 2197.00 cd  | 2407.00 b               |                          |                      |
|                                    | 3                              | 1986.33 de                    | 1843.33 d-f | 1525.33 e-g | 1785.00 c               |                          |                      |
| NPK Fertilizer + Amino acid        | 0                              | 1174.67 e                     | 1202.00 e   | 1426.00 e   |                         | 1267.56 c                |                      |
|                                    | 100                            | 2542.50 b                     | 3208.67 a   | 3327.17 a   |                         | 3026.11 a                |                      |
|                                    | 150                            | 2270.00 bc                    | 2156.83 cd  | 1861.17 d   |                         | 2096.00 b                |                      |
| Bio Health + Amino acid            | 0                              | 1683.22 b                     | 1830.00 b   | 1920.33 b   |                         |                          | 1811.19 b            |
|                                    | 3                              | 2308.22 a                     | 2548.33 a   | 2489.22 a   |                         |                          | 2448.59 a            |
| Effect of Amino acid               |                                | 1998.72 b                     | 2189.17 a   | 2204.78 a   |                         |                          |                      |

• Treatments sharing the same letter do not differ significantly from each other at the 5% probability level.

The binary interaction between NPK and Bio Health extract showed the superiority of the treatment combining fertilization at 100 kg·ha<sup>-1</sup> with 3 kg·ha<sup>-1</sup> Bio Health, recording the highest significant value of 4063.11 flower·plant<sup>-1</sup>, while the control treatment recorded the lowest significant value of 1037.44 flower·plant<sup>-1</sup>. The binary interaction between NPK and amino acid extract also showed the superiority of the 100 kg·ha<sup>-1</sup> treatment combined with 2.5 ml·L<sup>-1</sup> amino acid spraying,

reaching 3327.17 flower·plant<sup>-1</sup>, while the control treatment recorded the lowest value of 1174.67 flower·plant<sup>-1</sup>. The binary interaction between Bio Health extract and amino acid extract showed the superiority of the treatment combining 3 kg·ha<sup>-1</sup> Bio Health with amino acid spraying at (1.5 and 2.5) ml·L<sup>-1</sup>, recording the two highest significant values of (2548.33 and 2489.22) flower·plant<sup>-1</sup>, respectively, while the control treatment recorded the lowest value of 1683.22 flower·plant<sup>-1</sup>.

Regarding the triple interaction treatments among the studied factors, the treatment combining NPK fertilization at 100 kg·ha<sup>-1</sup> with the addition of 3 kg·ha<sup>-1</sup> Bio Health extract and spraying with amino acid extract at (1.5 and 2.5) ml·L<sup>-1</sup> achieved the two highest significant values of (4379.67 and 4312.00) flower·plant<sup>-1</sup>, respectively, while the control treatment recorded the lowest significant value of 908.67 flower·plant<sup>-1</sup>.

The results showed a large and clear effect of NPK, as fertilization at a rate of 100 kg·ha<sup>-1</sup> achieved the highest significant value of 3026.11 flower·plant<sup>-1</sup> compared to the unfertilized treatment, which recorded only 1267.56 flower·plant<sup>-1</sup> - more than double the number of flowers, providing clear practical evidence of the reflection of improved vegetative growth (leaf area and chlorophyll) on the reproductive stage through the source–sink relationship (Taiz *et al.*, 2022). Bio Health raised the value from 1811.19 to 2448.59 flower·plant<sup>-1</sup>, while amino acids at 2.5 ml·L<sup>-1</sup> achieved the highest value (2204.78) compared to 1995.72 flowers without addition.

### Total Yield (kg·ha<sup>-1</sup>)

The data in Table (8) show significant differences in total yield of borage (*B. officinalis* L.) as a result of NPK fertilizer, Bio Health extract, and amino acid extract. The two levels of 100 and 150 kg·ha<sup>-1</sup> NPK achieved the best significant values of (423.08 and 466.58) kg·ha<sup>-1</sup>, respectively, while the unfertilized treatment recorded the lowest significant value of 349.58 kg·ha<sup>-1</sup>. The results also showed that the Bio Health treatment at 3 kg·ha<sup>-1</sup> achieved the highest significant value for total yield of 437.97 kg·ha<sup>-1</sup>, outperforming the treatment without fertilizer addition, which recorded 388.19 kg·ha<sup>-1</sup>. As for amino acid extract, spraying at (1.5 and 2.5) ml·L<sup>-1</sup> achieved the highest significant values for total yield of (421.60 and 452.30) kg·ha<sup>-1</sup>, respectively, while the unsprayed treatment recorded the lowest significant value of 365.34 kg·ha<sup>-1</sup>.

**Table (8). Effect of NPK fertilizer, Bio Health extract, and amino acid extract on total yield (kg·ha<sup>-1</sup>) of borage (*B. officinalis* L.)**

| NPK Fertilizer<br>kg ha <sup>-1</sup> | Bio Health<br>kg ha <sup>-1</sup> | Amino acid ml L <sup>-1</sup> |            |            | Fertilizer + Bio Health | Effect of NPK Fertilizer | Effect of Bio Health |
|---------------------------------------|-----------------------------------|-------------------------------|------------|------------|-------------------------|--------------------------|----------------------|
|                                       |                                   | 0                             | 1.5        | 2.5        |                         |                          |                      |
| 0                                     | 0                                 | 290.28 f                      | 321.73 ef  | 323.96 ef  | 311.99 c                |                          |                      |
|                                       | 3                                 | 334.46 d-f                    | 361.27 c-f | 465.81 a-c | 387.18 b                |                          |                      |
| 100                                   | 0                                 | 403.98 a-e                    | 418.06 a-e | 437.42 a-d | 419.82 b                |                          |                      |
|                                       | 3                                 | 312.54 ef                     | 477.66 ab  | 488.81 a   | 426.34 b                |                          |                      |
| 150                                   | 0                                 | 374.76 b-f                    | 439.41 a-d | 484.12 ab  | 432.76 b                |                          |                      |
|                                       | 3                                 | 476.02 ab                     | 511.46 a   | 513.69 a   | 500.39 a                |                          |                      |
| NPK Fertilizer + Amino acid           | 0                                 | 312.37 e                      | 341.50 de  | 394.89 b-d |                         | 349.58 b                 |                      |
|                                       | 100                               | 358.26 c-e                    | 447.86 ab  | 463.11 ab  |                         | 423.08 a                 |                      |
|                                       | 150                               | 425.39 a-c                    | 475.43 s   | 498.90 a   |                         | 466.58 a                 |                      |
| Bio Health + Amino acid               | 0                                 | 356.34 c                      | 393.07 bc  | 415.16 bc  |                         |                          | 388.19 b             |
|                                       | 3                                 | 374.34 c                      | 450.13 ab  | 489.44 a   |                         |                          | 437.97 a             |
| Effect of Amino acid                  |                                   | 365.34 b                      | 421.60 a   | 452.30 a   |                         |                          |                      |

• Treatments sharing the same letter do not differ significantly from each other at the 5% probability level.

The binary interaction showed significant differences among the studied treatments in total yield, with the treatment combining 150 kg·ha<sup>-1</sup> NPK and 3 kg·ha<sup>-1</sup> Bio Health recording the highest significant value of 500.39 kg·ha<sup>-1</sup>, while the control treatment recorded the lowest significant value of 311.99 kg·ha<sup>-1</sup>. The binary interaction with NPK also had a significant effect, with the treatment combining 150 kg·ha<sup>-1</sup> NPK and amino acids at (1.5 and 2.5) ml·L<sup>-1</sup> achieving the highest significant values for total yield of (475.43 and 498.90) kg·ha<sup>-1</sup>, respectively, while the control treatment gave the lowest significant values of 312.37 kg·ha<sup>-1</sup>. The binary interaction treatments combining Bio Health extract at 3 kg·ha<sup>-1</sup> with amino acid extract at 2.5 ml·L<sup>-1</sup> recorded the highest significant value for total yield of 489.44 kg·ha<sup>-1</sup>, while the control treatment recorded the lowest significant value of 356.34 kg·ha<sup>-1</sup>.

The triple interaction between NPK, Bio Health, and amino acids also showed a significant effect on total yield, with the treatment combining 150 kg·ha<sup>-1</sup> NPK, 3 kg·ha<sup>-1</sup> Bio Health, and 2.5 ml·L<sup>-1</sup> amino acid spraying achieving the highest total yield of 513.69 kg·ha<sup>-1</sup>, while the control treatment recorded the lowest total yield of 290.28 kg·ha<sup>-1</sup>.

#### 4. General Discussion

The study results, as shown in Tables (2, 3, 4, 5, 6, 7, 8), demonstrated that NPK fertilizer addition, especially at the 100 and 150 kg·ha<sup>-1</sup> levels, improved most vegetative and root growth traits, yield, and chemical characteristics of borage, with the degree of response varying according to the trait studied. This is attributed to the functional integration among nitrogen, phosphorus, and potassium; nitrogen is incorporated into the formation of chlorophyll, amino acids, enzymes, and nucleic acids, thereby enhancing photosynthesis, dry matter formation, and vegetative growth. **Al-Nuaimi (1999)** showed that efficient nitrogen nutrition increases leaf area, the duration of its metabolic activity, and the rate of dry matter accumulation, while **Hawkesford et al. (2023)** indicated that nitrogen is one of the most influential elements in determining vegetative growth under limited mineral nutrition.

Phosphorus plays an essential role in cellular energy transfer through ATP, in the construction of nucleic acids and cell membranes, and in stimulating root growth, thereby enhancing water and nutrient absorption efficiency; **Taiz et al. (2015)** noted the importance of phosphorus in metabolic processes related to energy transfer, while **Lambers and Oliveira (2024)** showed that improved root growth resulting from phosphorus availability is reflected in shoot growth by improving the supply of water and mineral elements to the aerial parts. Potassium also contributed to improving growth through its role in activating enzymes, regulating osmotic pressure, controlling stomatal opening and closing, and improving sugar transport; **Wang and Wu (2013)** explained its role in regulating cellular signals related to growth and sugar transport to developing tissues, while **Zörb et al. (2014)** confirmed that its adequacy enhances water- and nutrient-use efficiency and dry matter accumulation. **Fageria (2024)** and **Lambers and Oliveira (2024)** also showed that the varying response of morphological traits to fertilization levels is related to differences in the plant's physiological priorities during its growth stages. These results are consistent with the findings of **Mahmoodi et al. (2018)**, who found that improving mineral nutrition in borage increased the plant's physiological efficiency and raised its productivity, which reinforces the interpretation of the results obtained in the current study and confirms that the positive vegetative growth response is linked to improved metabolic processes regulated by macronutrients.

The efficiency of the plant's response also increased when Bio Health WSG interacted with mineral fertilization. These results can be explained by the fact that Bio Health does not act only as a source of nutrients, but rather as a multicomponent biostimulant, combining humic acids, seaweed extract, and beneficial microorganisms — components that work in an integrated manner to improve the plant's physiological and metabolic processes, rather than simply increasing the amount of absorbed nutrients. **Rouphael and Colla (2020)** showed that modern biostimulants improve plant growth by raising nutrient-use efficiency, increasing photosynthetic efficiency, and regulating hormonal activity, rather than by substituting for mineral fertilizers **Al-Hatem (2025)**. Much of this response is attributed to the humic acids present in the product, as recent studies have proven that these compounds do not

only affect soil properties but also have direct effects on plant physiology. They stimulate the activity of the proton pump ( $H^+$ -ATPase) in root cell membranes, which increases the absorption of nitrates, phosphorus, potassium, and micronutrients, and they also enhance the formation of lateral roots and root hairs, which increases the surface area in contact with the soil and raises absorption efficiency. **El-Khayat (2024)**, in a study conducted on borage, showed that adding humic acids improved vegetative growth, yield, and oil content, attributing this to improved nutrient absorption and increased photosynthetic efficiency, while **Atiyeh et al. (2002)** showed that humic acids have an auxin-like effect, stimulating cell division and elongation and increasing root activity, which is directly reflected in increased plant biomass. These results support the clear improvement in vegetative growth traits observed in the current study upon the addition of Bio Health WSG.

The study results showed that foliar spraying with amino acids contributed to improving several vegetative growth traits of borage, although the degree of response varied among traits, with significant increases appearing in some growth indicators while the response was less pronounced in others. This variation reflects the nature of amino acid action, as they do not function as a conventional mineral fertilizer but rather act as biostimulants that influence the efficiency of metabolic processes and the plant's utilization of nutrients and energy. **Carillo et al. (2021)** showed that protein hydrolysates and amino acids do not only supply the plant with nitrogen but also activate the metabolic pathways responsible for growth, raise nutrient-use efficiency, and improve the plant's physiological performance, which is reflected in increased vegetative growth. **Deveikytė et al. (2025)** also showed that spraying with amino acids increased vegetative growth, chlorophyll content, and antioxidant activity in basil, as a result of improved vital processes within the plant, consistent with the general trend of the current results.

The effect of amino acids in improving growth is attributed to their direct involvement in the construction of proteins and enzymes, which reduces the energy the plant expends in synthesizing them internally **Al-Hatem et al. (2026)**. The plant normally needs to fix inorganic nitrogen and convert it into amino acids before it can be used in protein synthesis, a process that consumes a considerable amount of energy stored as ATP and NADPH. When amino acids are supplied directly through foliar spraying, the plant can redirect part of this energy toward cell division, cell elongation, and biomass formation. **Taiz et al. (2022)** confirm that providing ready-made organic compounds reduces the metabolic burden on the plant and allows energy to be directed toward growth and development processes, particularly during rapid growth stages.

One of the important mechanisms explaining the increase in leaf area and number of leaves is that certain amino acids, such as glutamic acid and glycine, serve as key hubs in nitrogen metabolism within the plant, as they are involved in the formation of most other amino acids and participate in the synthesis of chlorophyll, proteins, and nucleotides. **Buchanan et al. (2015)** indicate that glutamine and glutamic acid represent the starting point in most nitrogen assimilation reactions, and that their increased availability accelerates the synthesis of proteins and enzymes necessary for cell division and leaf growth. **Carillo et al. (2021)** also showed that plant protein hydrolysates increase the activity of nitrogen metabolism enzymes, thereby improving vegetative growth.

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*Note: The remaining English-language references cited throughout the text (Slama et al., Stearn, Ibrahim and Alshammaa, Latoch et al., Casas-Cardoso et al., Sytar et al., Mehrabani et al., Hawkesford et al., Fageria, Lambers and Oliveira, Wang and Wu, Zörb et al., Al-Mohammad et al., Rouphael and Colla, Alharbi et al., Ekin et al., Andrzejak et al., Sun et al., Alhasan et al., El-Nakhel et al., Henderson et al., Ibrahim et al., Taiz et al., Mahmoodi et al., El-Khayat, Atiyeh et al., Carillo et al., Deveikytė et al., and Buchanan et al.) were already in English/Latin script in the source document and are reproduced here as originally written; their full bibliographic entries were not included in the reference list of the source file.*