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RESEARCH ARTICLE
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Sustainable Boost for Greenhouse Cucumbers: Integrating Amino Acids with Vermicompost to Enhance Growth and Quality

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ABSTRACT

Cucumber (*Cucumis sativus* L.) is an economically important horticultural crop, extensively grown for its high nutritional value, rapid growth, and notable yield potential. The integration of foliar-applied amino acids with soil-incorporated vermicompost may offer a sustainable approach to improve cucumber yield and quality in greenhouse cultivation systems. Therefore, this study was conducted to evaluate the individual and combined effects of foliar-applied amino acids and soil-applied vermicompost, in comparison to NPK fertilization, on the growth performance, mineral composition, and biochemical responses of cucumber under greenhouse conditions. The experiment was conducted using a randomized complete block design with nine treatments, including NPK fertilization, three vermicompost rates (7.5, 15, and 30t/ha), amino acids (50% w/w) and their combinations, with four replications. Results revealed that NPK and the combined application of high-rate vermicompost with amino acids (V3+AA) significantly enhanced shoot fresh and dry weight, fruit number, and fruit weight per plant compared with other treatments. These treatments also resulted in the highest nitrogen, phosphorus, and potassium content in plant tissues, while plant calcium content was particularly enhanced by V3+AA compared to NPK, amino acids alone (AA) treatment and the control. In contrast, magnesium content was highest in control plants and lowest under NPK. DPPH radical scavenging activity, total flavonoid content, and total phenolic content were significantly improved by NPK and V3+AA. The results demonstrated that integrating vermicompost with foliar-applied amino acids can achieve productivity and quality comparable to conventional mineral fertilization in greenhouse cucumber cultivation. This approach offers a sustainable alternative by reducing reliance on synthetic fertilizers while enhancing nutrient cycling and supporting soil, plant, and human health.

Keywords: Amino acids, Cucumber, Greenhouse production, Sustainable production, Vermicompost.

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INTRODUCTION

Greenhouse vegetable production has expanded rapidly worldwide as a strategic response to increasing food demand, climate change impacts, and land and water limitations. By enabling year-round cultivation, higher yields, and improved product quality, protected cultivation systems play a critical role in global food security, particularly in arid and semi-arid regions (Argento et al., 2024). However, despite these advantages, greenhouse vegetable production faces growing challenges related to environmental sustainability, resource use efficiency, and climate resilience. Recent assessments highlighted that the intensive nature of greenhouse systems often leads to excessive inputs of energy, water, and fertilizers, thereby increasing production costs and environmental footprints

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(Rosenzweig et al., 2020; Gruda et al., 2024). The intensive use of chemical fertilizers in modern agricultural systems has raised serious environmental concerns, particularly under intensive greenhouse production. Excessive fertilizer application is closely associated with nutrient leaching into water bodies, soil acidification, salinity buildup and the decline of soil organic matter and microbial activity, ultimately reducing soil fertility and sustainability (Fan et al., 2020; Yan et al., 2024), in addition to increased greenhouse gas emissions, especially nitrous oxide (N_2O), which has a global warming potential substantially higher than that of carbon dioxide (CO_2), thereby contributing to climate change (Singh, 2024). These environmental impacts are particularly severe in arid and semi-arid regions, such as Jordan, where limited water availability and fragile soil systems amplify nutrient losses and degradation processes under intensive fertilization regimes (Taha et al., 2020; Argento et al., 2024).

Organic amendments and biostimulants have gained increasing attention as sustainable tools for improving crop productivity while mitigating the environmental impacts associated with intensive agricultural systems (Mulatu & Bayata, 2024; Hasddin & Ulyasniati, 2025). Organic amendments, such as composts and vermicompost, contribute to the improvement of soil physical structure, nutrient retention capacity, and biological activity, thereby enhancing nutrient availability and long-term soil fertility. In parallel, biostimulants act primarily by stimulating plant physiological and biochemical processes, including nutrient uptake efficiency, photosynthetic performance, and stress tolerance. Recent studies indicated that the combined use of organic amendments and biostimulants can generate synergistic effects, leading to improved crop growth, yield, and quality while reducing dependence on mineral fertilizers and associated environmental risks (Hadi & Al-juthery, 2025; Hasddin & Ulyasniati, 2025).

Amino acids applied as foliar biostimulants are considered environmentally friendly and safe for plant, soil, and human health due to their natural origin, low application rates, rapid uptake and high efficiency. The biostimulatory effect of amino acids on plant growth and nutrient uptake have been frequently reported. Many studies confirmed that that foliar application of amino acids, either alone or in combination with essential nutrients, enhances plant morphological and physiological traits, while also mitigating the adverse effects of some environmental stresses (Shooshtari et al., 2020; Marium et al., 2021; García-Cano et al., 2025). El-Beltagi et al. (2023) reported that foliar application of amino acid biostimulants and CMS (liquid yeast waste) significantly enhanced broccoli growth, physiological performance, and yield, particularly under moderate water stress. Amino acid treatments improved chlorophyll content, nutrient uptake, and overall stress tolerance. The highest yield was obtained with irrigation every 5 days combined with CMS, while the lowest yield occurred under a 15-day irrigation interval without CMS.

Vermicompost is an organic material produced through a non-thermophilic process involving the synergistic activity of earthworms and microorganisms during the decomposition of organic waste. It contains essential macro- and micronutrients which promotes photosynthesis, increases chlorophyll content, and improves the nutrient composition of plant tissues (Olowoake et al., 2021; Jankauskienė et al., 2022; Al-Al-Maamori et al., 2023; Mulatu & Bayata, 2024). Moreover, vermicompost has been shown to enhance soil physical, chemical, and biological properties by increasing organic matter content, improving soil structure, and promoting beneficial microbial activity, which in turn enhance nutrient retention and availability to plants, ultimately**,** increasing plant growth and productivity (Esmaielpour et al., 2020; Olowoake et al., 2021; Piri et al., 2022; Kocaman et al., 2024; Al-Tufaili et al., 2025; Hadi & Al-juthery, 2025). Olowoake et al. (2021) demonstrated that vermicompost application significantly improved soil chemical properties, nutrient uptake, and cucumber yield compared with NPK fertilization and the unfertilized control. Vermicompost supplying 90 kg N ha^{-1} produced the highest vegetative growth and fruit yield and showed clear residual benefits by increasing soil pH, organic carbon, and available P and K in the subsequent cropping cycle. A more recent study of Al-Tufaili et al. (2025) investigated the effect of foliar applications of vermicompost and amino acids on growth and yield of eggplant (*Solanum melongena* L) under field conditions. The study evaluated three concentrations of vermicompost (0, 25 and 50mL/L) and three levels of a commercial amino acid formulation (0, 1.5, and 2mL/L), applied individually and in combination. The results demonstrated that higher application rates of vermicompost (50 mL/L), amino acids (2mL/L) and combined application treatment significantly enhanced plant growth and yield components.

Cucumber (*Cucumis sativus* L.) is an economically significant horticultural crop cultivated globally for its high nutritional value, rapid growth and ability to produce high yields particularly in greenhouse conditions (Shooshtari et al., 2020). Optimizing the productivity and quality of cucumber under intensive cultivation remains a major challenge, especially under abiotic stresses such as salinity, nutrient deficiencies, and limited water availability (Taha et al., 2020; Yan et al., 2024). These constraints highlight the need for sustainable management strategies that enhance plant performance while reducing reliance on conventional high-input fertilization practices.

Despite the growing body of literature on vermicompost and amino acids, their combined application as an integrated nutrient management strategy for greenhouse cucumbers has received limited attention, particularly in comparison with conventional NPK fertilization. Moreover, information remains scarce regarding their effects on plant mineral nutrient composition, secondary nutrient dynamics, and biochemical quality traits under greenhouse conditions. Therefore, this study aimed to evaluate the individual and synergistic effects of soil-applied vermicompost and foliar-applied amino acids, compared with conventional NPK fertilization, on the growth performance, mineral composition, and biochemical responses of cucumber (*Cucumis sativus* L.) under greenhouse conditions. It was hypothesized that the combined application would enhance productivity and quality compared with single-input treatments and conventional NPK fertilization.

MATERIALS & METHODS

Experiment Location

The experiment was conducted during the 2022 growing season under greenhouse conditions at the Agricultural Research Center, Faculty of Agriculture, Jordan University of Science and Technology (JUST), Irbid Governorate, Jordan (32°29′43.1″ N, 35°59′29.8″ E) (Fig. 1). During the growing season, the mean daytime temperature ranged between 21 and 35°C and nighttime temperature between 11 and 20°C, while relative humidity ranged from 45 and 59%. Plants were grown under natural daylight conditions without supplemental lighting.

Experiment Design

The experiment was carried out using a randomized complete block design (RCBD) to minimize variability and ensure robust statistical analysis. Nine treatments were evaluated with four replications per treatment, resulting in a total of 36 experimental units.

Treatments and Applications

Three main treatment factors were examined: amino acids, vermicompost, and NPK fertilizer. Amino acids (50% w/w) were applied as a foliar spray at 3mL/L, starting two weeks after transplanting and repeated biweekly for a total of five applications. The amino acid source was a commercial organic formulation known as Fert One (Agrimatco, UAE) comprising 8% organic nitrogen and 50% total amino acids. Vermicompost was incorporated into the soil at three application rates: 7.5t/ha (V1), 15t/ha (V2), and 30t/ha (V3), equivalent to 23.60, 47.10, and 94.20g/pot, respectively. The physical and chemical properties of both the soil and vermicompost used are presented in Table 1.

Table 1: The chemical properties of the soils and vermicompost used in this study (*n* = 3)

Parameter	Soil	Vermicompost
N (%)	0.072	1.37
P (mg/kg)	1.42	1229.5
K (mg/kg)	54.95	1519.0
Mg (mg/kg)	228.0	11413.0
Ca (mg/kg)	1512.76	10894.0
Na (mg/kg)	419.65	197.7
Organic matter (%)	3.422	82.60
C:N ratio	27.63	37:1

N=Nitrogen; P=phosphorus; K=potassium; Mg=magnesium; Ca=calcium; Na=sodium. C:N ratio=carbon-to-nitrogen ratio. mg/kg=milligram per kilogram.

The NPK fertilizer (20:20:20) was dissolved in water at a concentration of 2g/L and applied via irrigation. Treatments included individual and combined applications of these inputs, as well as control and chemical-only treatments.

Planting and Irrigation Management

Cucumber seeds (*Cucumis sativus* L.) of the cultivar Shaam F1 were used in this experiment. Uniform and healthy seedlings were raised under greenhouse conditions prior to transplanting. Seedlings were transplanted into pots (20 × 20cm) filled with the prepared growth medium. No sterilization procedures were applied to the growth medium prior to planting. The pots were arranged on greenhouse benches under natural daylight conditions and were equipped with drainage holes at the bottom to allow excess irrigation water to drain freely and prevent waterlogging. Standard greenhouse management practices were applied throughout the growing season to maintain optimal plant growth and health. Irrigation was applied uniformly to all treatments using equal quantities of tap water to maintain the moisture content of the growth media close to field capacity, as determined according to the method described by Almaz et al. (2023).

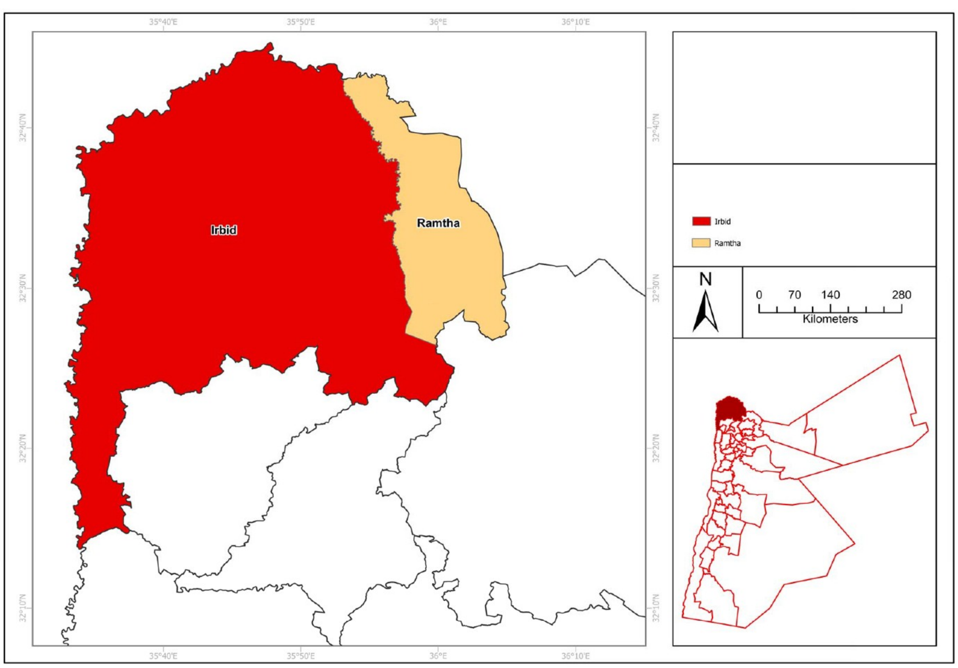

Fig. 1: Geographic location of the experimental site at the Agricultural Research Center, Faculty of Agriculture, Jordan University of Science and Technology (JUST), Irbid Governorate, northern Jordan, showing the position of the study area within Jordan and the administrative boundaries of the region.

Measurements and Data Recorded

Morphological data were recorded at harvest, including shoot fresh and dry weights, the number of fruits per plant and their total weight were recorded upon ripening. An analytical balance with precision of 0.001g was used in all mass measurements.

The determination of the total plant nitrogen, phosphorus, potassium, calcium and magnesium content was carried out as described by AOAC (1995). The antioxidant activity of cucumber fruits extracts was measured using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay as described by Brands-Williams et al. (1995). Flavonoid content was determined by a colorimetric method as described by Zhishen et al. (1999). Total phenols in cucumber fruits were determined using the Folin–Ciocalteu reagent, with gallic acid as a standard for constructing the calibration curve (Slinkard & Singleton, 1977). The media and soil analysis used in this study has been previously reported (Alomari et al., 2024). The same batches were used here; vermicompost chemical properties were determined prior to the experiment through laboratory analysis at the Faculty of Agriculture, Jordan University of Science and Technology, which consist of the determination of the total nitrogen that was carried out using the Kjeldahl method as described by the Association of Official Agricultural Chemists (AOAC, 1995). The determination of the available Phosphorus that was carried out using Olsen method (pH8.5, 0.5M $NaHCO_3$) as described by FAO (2021). Determination of sodium and potassium Content, standard curves that were prepared by using standard solutions of known concentrations of both sodium and potassium on flame photometer (BWB-xp). Concentrations of both sodium and potassium were directly obtained from a constructed standard curve (AOAC, 1995). Determination of magnesium and calcium content, extraction of exchangeable magnesium and calcium from the soil and other substrates with pH7, 1M NH4 acetate as described by Jones (2000). Determination of organic matter was carried out using Loss of weight on ignition method as described by Motsara and Roy (2008). Samples of the growth medium from each treatment were collected prior to planting, oven-dried at 70°C, and passed through a 2mm sieve for physicochemical analysis. Electrical conductivity (EC) and pH were subsequently measured in saturated paste extracts using EC and pH meters following the procedures described by Motsara and Roy (2008).

Statistical Analysis

All collected data were subjected to analysis of variance (ANOVA) using SAS software version 9.4 (2013). The Least Significant Difference (LSD) test 5% significance level was used to calculate the differences among the mean values.

RESULTS & DISCUSSION

Plant Fresh and Dry Weight

Results presented in Fig. 2 demonstrated that shoot fresh and dry weight of cucumber were significantly affected by the applied treatments ($p<0.001$). All treatments significantly increased shoot fresh and dry weight compared with the control, except for the lower vermicompost rates (V1 and V2), which did not show significant differences from the control. The highest shoot fresh and dry weight were recorded under NPK fertilization, confirming the strong capacity of mineral fertilizers to enhance vegetative biomass accumulation under greenhouse conditions. This response can be attributed to the balanced and readily available supply of nitrogen, phosphorus, and potassium, which collectively support key physiological processes, including photosynthetic activity, protein synthesis, and osmotic regulation. Nitrogen plays a central role in chlorophyll formation and amino acid synthesis, phosphorus supports energy transfer and nucleic acid metabolism, and potassium regulates enzyme activation and cell turgor, thereby promoting shoot expansion and dry matter accumulation.

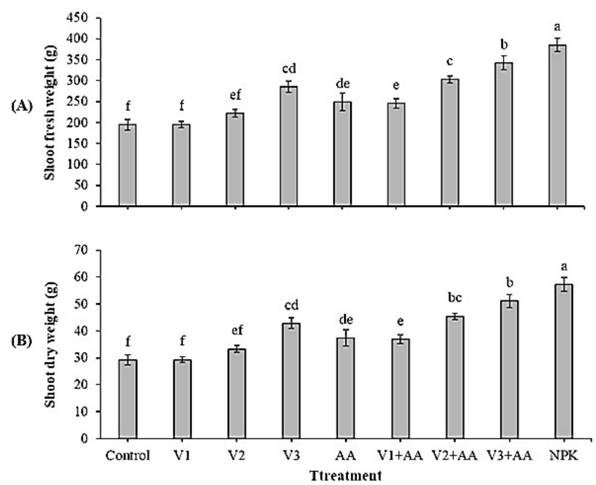

Fig. 2: Effect of foliar-applied amino acids and soil-applied vermicompost and their combination on shoot fresh and dry weight of cucumber plants. Bars represent mean ± standard error (*n* = 4). Different letters indicate significant differences at $p<0.05$. (LSD: shoot fresh weight =39.04 and dry weight =5.88).

Similar increases in plant biomass under mineral fertilization have been reported in cucumber and tomato (Jilani et al., 2009; Shooshtari et al., 2020; Mohammed et al., 2021; Bentamra et al., 2023; Yadav et al., 2025). Shooshtari et al. (2020) compared different glycine application methods (soil and foliar) with conventional NPK fertilization and reported that soil application of glycine at higher rates and NPK significantly increased plant height and total shoot dry weight relative to the control and most foliar glycine treatments. NPK provided a strong and reliable increase in shoot biomass, reflecting its capacity to supply nutrients in forms that are immediately available for uptake and assimilation. The authors attributed the superior dry weight accumulation under NPK primarily to enhanced nitrogen availability and improved overall nutrient balance, which supported sustained vegetative growth throughout the cropping period.

Despite the superiority of NPK, the combined application of the highest vermicompost rate with amino acids (V3+AA) resulted in a marked increase in both shoot fresh and dry weight, ranking second among all treatments. Comparable responses have been reported in recent cucumber studies, where foliar application of amino acids significantly increased shoot biomass, leaf area, and dry matter accumulation under protected cultivation (Zargar Shoshtari et al., 2023). Similarly, amino-acid-based biostimulants were shown to enhance vegetative growth by improving photosynthetic performance and nitrogen metabolism, particularly when combined with adequate nutrient supply (Marium et al., 2021). In addition, vermicompost application has been reported to significantly increase shoot fresh and dry weight in cucumber by improving soil physical and chemical properties and stimulating root development (Esmaielpour et al., 2020; Rani, 2024). The relatively limited response observed under the lower vermicompost rates (V1 and V2) suggests that insufficient organic input may not provide adequate nutrient availability or microbial stimulation to support substantial biomass accumulation. This dose-dependent effect of vermicompost has been documented in recent studies, which demonstrated that higher application rates are necessary to achieve significant improvements in plant growth (Acharya et al., 2024; Rani, 2024).

The enhanced shoot biomass under the V3+AA treatment can be explained by improved nitrogen use efficiency and metabolic activity. Exogenously applied amino acids can be directly incorporated into protein synthesis or act as signaling molecules that stimulate enzymatic activity, hormonal balance, and photosynthetic efficiency. Recent evidence confirmed that amino-acid-based biostimulants increase chlorophyll content, stomatal conductance, and carbon assimilation efficiency, leading to greater biomass accumulation in cucumber and other vegetable crops (El-Beltagi et al., 2023). From a sustainability perspective, although NPK fertilization could be more effective in maximizing shoot biomass, the substantial increase observed under the integrated vermicompost and amino acid treatment could be a viable alternative for reducing mineral fertilizer inputs. Such integrated approaches align with sustainable greenhouse production by improving nutrient use efficiency, enhancing soil biological activity, and promoting the recycling of organic wastes, while maintaining high levels of vegetative growth and productivity.

Minerals Content

The mineral composition of cucumber shoots was significantly affected by the applied treatments, as presented in Table 2. All fertilized treatments resulted in a clear increase in nitrogen (N) content relative to the control, indicating improved nitrogen acquisition under both mineral and organic nutrient inputs. The highest nitrogen concentration was observed under NPK fertilization, while the lowest value was recorded in the untreated control. This pattern reflects the direct availability of inorganic nitrogen forms supplied by mineral fertilizers, which are readily absorbed by plant roots and rapidly incorporated into vegetative tissues. The observed increase in shoot nitrogen content under NPK fertilization is consistent with previous findings in cucumber, where mineral nutrient application significantly enhanced leaf and shoot nitrogen concentrations compared with unfertilized plants (Jilani et al., 2009; Shooshtari et al., 2020). In addition to mineral fertilization, treatments involving vermicompost and amino acids also showed increased nitrogen content relative to the control, although to a lesser extent than NPK. This suggests that organic amendments can enhance nitrogen availability through gradual mineralization and improved nutrient retention, while amino acids may contribute to nitrogen assimilation efficiency by providing readily usable organic nitrogen forms and stimulating enzymatic activity involved in nitrogen metabolism (Marium et al., 2021; Al-Maamori et al., 2023; Mulatu & Bayata, 2024).

Table 2: Effect of amino acids and vermicompost on nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) content in cucumber plants (*n* = 4)

Treatment	N (%)	P (mg/g)	K (mg/g)	Ca (mg/g)	Mg (mg/g)
Control	1.36^{g}	7.05^{c}	32.64^{e}	7.04^{de}	18.70^{a}
V1	1.72^{f}	7.04^{c}	37.06^{de}	10.97^{cd}	18.43^{a}
V2	1.92^{ef}	7.39^{bc}	41.61^{bcd}	11.94^{bcd}	15.15^{ab}
V3	2.16^{de}	7.80^{ab}	45.64^{ab}	16.59^{ab}	15.94^{ab}
AA	2.44^{bcd}	6.31^{d}	37.94^{cde}	5.72^{e}	13.14^{bc}
V1+AA	2.41^{cd}	7.05^{c}	42.62^{bcd}	9.35^{de}	13.32^{bc}
V2+AA	2.57^{cb}	7.08^{c}	44.09^{abc}	14.96^{abc}	15.80^{ab}
V3+AA	2.77^{ab}	7.13^{bc}	46.12^{ab}	18.68^{a}	15.65^{ab}
NPK	2.91^{a}	8.35^{a}	50.73^{a}	5.26^{e}	9.66^{c}
LSD	0.33	0.69	6.94	5.00	4.49

Means with different letters in the same column are significantly different ($p<0.05$). AA=foliar amino acids application at 3mL/L; V1=vermicompost applied at 7.5t/ha; V2=vermicompost applied at 15t/ha; V3=vermicompost applied at 30t/ha; V1+AA, V2+AA, V3+AA=combined vermicompost and amino acid treatments; NPK=mineral fertilization; N=nitrogen; P=phosphorus; K=potassium; Ca=calcium; Mg=magnesium; LSD=least significant difference; mg/g=milligrams per gram.

Phosphorus (P) content in cucumber shoots was significantly affected by the applied treatments (Table 2). The highest phosphorus concentration was recorded under NPK fertilization, reflecting the high solubility and immediate bioavailability of mineral phosphorus sources, which facilitate rapid uptake and utilization by plants (Mohammed et al., 2021; Bentamra et al., 2023). In contrast, plants treated with amino acids alone (AA) exhibited the lowest phosphorus content (6.31mg/g). This response may indicate that foliar application of amino acids was insufficient to substantially enhance plant phosphorus accumulation in the absence of adequate soil phosphorus availability.

Vermicompost treatments, particularly at higher application rates and when combined with amino acids, resulted in intermediate to relatively high phosphorus levels, which can be attributed to the gradual mineralization of organic phosphorus and enhanced microbial activity that promotes phosphorus solubilization. Similar trends under vermicompost application have been reported in several studies on cucumber and other vegetable crops (Esmaielpour et al., 2020; Mulatu & Bayata, 2024; Rani, 2024).

Plants supplied with NPK exhibited the highest potassium (K) content, while treatments involving high vermicompost rates, either combined with amino acids (V3+AA) or alone (V3) achieved statistically comparable potassium levels. These treatments resulted in significantly higher potassium content compared to the control. Notably, the comparable potassium concentrations observed under V3, V3+AA, and V2+AA treatments suggest that vermicompost can effectively enhance potassium availability and uptake. This response may be explained by the inherent potassium content of vermicompost, its gradual nutrient release pattern, and its capacity to improve substrate cation exchange properties, thereby reducing potassium losses and sustaining potassium availability in the root zone (Acharya et al., 2024; Rani, 2024). The addition of amino acids may further enhance potassium uptake efficiency by stimulating root activity, membrane transport processes and overall nutrient acquisition (Marium et al., 2021; Sadak et al., 2023). While NPK mineral fertilizers resulted in the highest concentrations of nitrogen, phosphorus, and potassium, vermicompost treatments at higher rates and when combined with amino acids achieved comparable nutrient levels. This suggests that vermicompost can effectively serve as a partial replacement for synthetic fertilizers. Specifically, the high potassium levels achieved through vermicompost reflect improved nutrient retention and uptake efficiency without the need for mineral potassium inputs. Furthermore, the use of amino acids promotes sustainability by enhancing how plants assimilate nutrients by improving the efficiency of nutrient uptake and utilization.

Calcium (Ca) content in cucumber shoots differed significantly among treatments (Table 2). The highest vermicompost application rate combined with amino acids (V3+AA), resulted in increased calcium accumulation, followed by the highest vermicompost rate applied alone (V3). In contrast, plants receiving NPK fertilizer and AA treatment exhibited the lowest calcium concentration.

The enhanced calcium accumulation under higher vermicompost-based application can be attributed to several interacting mechanisms. Vermicompost supplies calcium directly and improves substrate physicochemical properties, including cation exchange capacity and moisture retention, which together promote calcium availability and uptake. In addition, the gradual nutrient release from organic amendments favors sustained calcium supply in the root zone, supporting continuous transport of calcium through the transpiration stream to developing shoot tissues. Similar increases in plant calcium content under vermicompost application have been reported in cucumber and other vegetable crops, where organic amendments improved calcium availability and plant uptake (Mahmud et al., 2020; Rani, 2024). Esmaielpour et al. (2020) Demonstrated that application of vermicompost (20–60%) increased amount of calcium in cucumber shoot, while the amount of calcium in 10% treatment was not significantly different with control. However, Keskin et al. (2025) reported that the combined application of amino acids and vermicompost on iceberg lettuce grown under greenhouse and soilless conditions using a tuff–zeolite medium did not significantly affect leaf calcium content, as values were statistically similar to those of the untreated control, while the foliar application of the combined amino acid and fulvic acid increased the calcium content by 50% compared to the control.

Unlike potassium and calcium, magnesium (Mg) content was increased in control plants and V1, while plants treated with NPK exhibited the lowest magnesium content among all treatments. This inverse trend, where high-input treatments such as NPK resulted in reduced magnesium accumulation, is likely due to nutrient antagonism, particularly between potassium and magnesium. Excessive potassium supplied through NPK fertilizers can competitively inhibit magnesium uptake by plant roots, indicating that the balanced use of potassium and magnesium fertilizers is necessary for sustaining high plant-available magnesium and alleviating potassium-induced magnesium deficiency (Yan et al., 2020; Chaudhry et al., 2021; Xie et al., 2021). Therefore, these results emphasize that both optimizing potassium supply and maintaining balanced K:Mg nutrition are essential for sustaining adequate plant magnesium status and minimizing potassium-induced magnesium depletion under greenhouse cucumber production.

Biochemical Analysis

The application of amino acids, vermicompost, and NPK fertilizers significantly affected the DPPH radical scavenging activity, total flavonoid (TFC) and total phenolic content (TPC) of cucumber plants, and exhibited similar response patterns across treatments (Table 3). The highest DPPH radical scavenging activity was observed in plants treated with NPK, followed by V3+AA and V3, indicating enhanced antioxidant potential under both mineral and high-dose organic treatments, while the control and V1 exhibited the lowest DPPH values. Similarly, the highest values for both total flavonoid and total phenolic content were observed in plants treated with NPK, recording 364.0mg/100g for flavonoid content and 480.5 mg/100g for phenolic content. This was followed by the V3+AA treatment, which resulted in flavonoid content and phenolic content values of 336.3mg/100g and 443.4mg/100g, respectively. The high content in these treatments may be attributed to improved nutrient availability and enhanced physiological activity, promoting the biosynthesis of phenolic compounds and flavonoids – key antioxidants in plant defense systems (Jang et al., 2021). In contrast, the lowest flavonoid content and phenolic content were observed in the control group (Table 3).

The enhancement of DPPH radical scavenging activity, total phenolic and flavonoid content under NPK fertilization and high vermicompost rate treatments reflects increased metabolic activity and secondary metabolite biosynthesis. Adequate nutrient availability supports carbon assimilation and provides the metabolic precursors required for phenylpropanoid pathway activation, resulting in elevated antioxidant production. Similar increases in antioxidant capacity under mineral fertilization and organic biostimulant-based systems have been reported previously, demonstrating that both readily available nutrients and biologically active organic amendments can stimulate antioxidant metabolism in vegetable crops (El-Beltagi et al., 2023; Keskin et al., 2025). In the current study, although NPK recorded the highest absolute antioxidant values, high-rate vermicompost treatments promoted antioxidant accumulation relative to the control, implying the capacity of organic fertilizers to stimulate secondary metabolism through biological rather than solely nutritional mechanisms.

Table 3: Effect of amino acids and vermicompost on DPPH radical scavenging activity, total flavonoid content (TFC) and total phenolic content (TPC) in cucumber plants (*n* = 4)

Treatment	DPPH (%)	TFC (mg/100g)	TPC (mg/100g)
Control	13.35^{d}	199.5^{d}	254.9^{d}
V1	13.43^{d}	228.2^{cd}	350.1^{c}
V2	15.20^{cd}	271.9^{bcd}	373.2^{bc}
V3	20.98^{a}	306.3^{abc}	404.2^{abc}
AA	16.63^{bcd}	243.8^{cd}	378.1^{bc}
V1+AA	14.98^{cd}	273.4^{bcd}	394.7^{abc}
V2+AA	17.48^{abc}	307.4^{abc}	388.0^{bc}
V3+AA	20.15^{ab}	336.3^{ab}	443.4^{ab}
NPK	21.23^{a}	364.0^{a}	480.5^{a}
LSD	3.94	84.7	89.2

Means with different letters in the same column are significantly different (p<0.05). AA=foliar amino acids application at 3mL/L; V1=vermicompost applied at 7.5t/ha; V2=vermicompost applied at 15t/ha; V3=vermicompost applied at 30t/ha; V1+AA, V2+AA, V3+AA=combined vermicompost and amino acid treatments; NPK=mineral fertilization; TFC=total flavonoid content; TPC=total phenolic content; LSD=least significant difference; Mg/100g= milligrams per 100 gram.

Media pH and EC

Data presented in Fig. 3A indicated that the pH of the cucumber growth medium was significantly influenced by the applied treatments ($p<0.001$). Across all treatments, the growth medium remained within a slightly to moderately alkaline range. A gradual decrease in pH was observed with increasing vermicompost application rates, indicating a dose-dependent acidifying effect. Similar reductions in growth medium pH following vermicompost application have been reported on several crops. This pH decline is commonly attributed to enhanced microbial activity associated with organic amendments, including the production of ammonium, carbon dioxide, and organic acids during organic matter degradation (Esmaielpour et al., 2020; Al-Maamori et al., 2023).

In the present study, the highest pH values were recorded in the control, V1, AA and V1+AA treatments, all of which remained within the alkaline range, whereas higher vermicompost rates and NPK fertilization resulted in a statistically significant decrease in pH values. From a nutrient-management perspective, such moderate pH reductions may improve nutrient availability, underscoring the agronomic value of vermicompost in regulating root-zone chemical conditions (Esmaielpour et al., 2020). The electrical conductivity (EC) of the cucumber growth medium was not significantly affected by the applied treatments (Fig. 3B), indicating that the amino acids, vermicompost and NPK treatments did not lead to substantial alterations in the soluble salt concentration of the growth media. However, a slight increase in EC was observed in the NPK (362.0μS/cm) treatment. In contrast, treatments with low nutrient input, such as AA alone (304.0μS/cm) and the control (309.3μS/cm), exhibited a slight decrease in EC values.

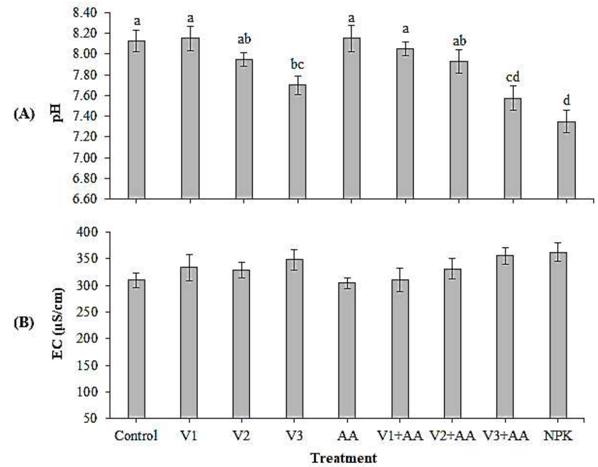

Fig. 3: Effect of foliar-applied amino acids and soil-applied vermicompost and their combination on pH (A) and EC (B) of the cucumber growth medium. Bars represent mean ± standard error (*n* = 4). Different letters indicate significant differences at p<0.05 (LSD: pH=0.29 and EC =NS).

Fruit Yield

The number of fruits (Fig. 4A) and fruit weight per cucumber plant (Fig. 4B) were significantly influenced by the applied treatments ($p<0.001$), with the highest values recorded in NPK and V3+AA treatments, which resulted in statistically similar outcomes, scoring 17.5 and 17.25 fruits per plant, and 1.36kg and 1.20kg fruit weight per plant,

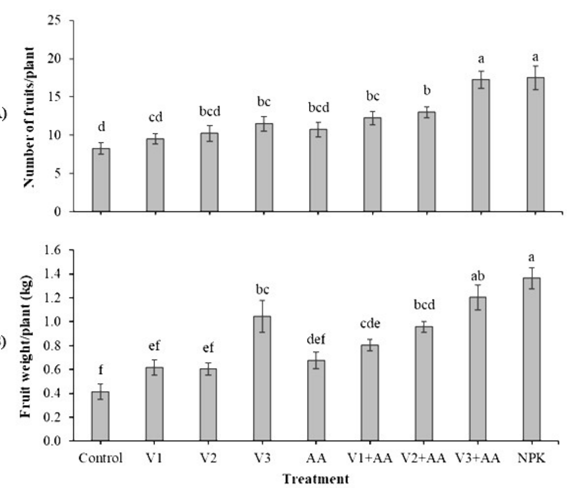

Fig. 4: Effect of foliar-applied amino acids and soil-applied vermicompost and their combination on number of fruits and fruit weight per plant of cucumber. Bars represent mean ± standard error (*n* = 4). Different letters indicate significant differences at p<0.05. (LSD: number of fruits/plant =3.00 and fruit weight/plant =0.29).

respectively, whereas the control plants exhibited the lowest fruit number average (8.25) and fruit weight (0.41kg). The superior yield performance under NPK fertilization reflects the direct and readily available supply of essential nutrients, which supports vegetative growth and productivity. Notably, the comparable performance of the V3+AA treatment indicates that high-rate vermicompost combined with amino acids can effectively enhance productivity. This response is likely due to improved nutrient availability and better assimilate partitioning toward reproductive organs under integrated organic and biostimulant inputs. Amino acids are known to stimulate physiological processes related to flowering and fruit development, while vermicompost improves nutrient retention and microbial activity in the root zone (Azarmi et al., 2008; Haghighi et al., 2020; Al-Tufaili et al., 2025). These findings align with those obtained by Shooshtari et al. (2020) who reported that cucumber plants treated with NPK, soil and foliar amino acids, especially glycine at a rate of 500ppm showed a significant increase in fruit number and fruit weight compared to the control. Keskin et al. (2025) Found that the combined application of amino acids and vermicompost on iceberg lettuce grown under greenhouse and soilless conditions increased the yield by 9.42% over the control.

Conclusions

In the present study, alongside chemical NPK fertilization, the combined application of high-dose vermicompost with amino acids (V3+AA) showed superior performance across most measured parameters, including shoot biomass, fruit yield, antioxidant activity, secondary metabolite accumulation, and mineral content, while V3+AA uniquely improved calcium accumulation. Although NPK was most effective in promoting overall plant growth and yield, the V3+AA treatment offered comparable results with added benefits to soil health and sustainability. The ability of vermicompost integrated with amino acids to approach the effectiveness of mineral fertilization has important implications for greenhouse cucumber production, where intensive fertilizer use is common. Such integrated practices can reduce reliance on synthetic fertilizers, thereby lowering greenhouse gas emissions, minimizing nutrient leaching and soil degradation, and improving soil organic matter and nutrient cycling. Moreover, given the high nutrient demand of modern greenhouse cucumber genotypes, the use of organic amendments and biostimulants as partial substitutes for chemical fertilizers represents a sustainable strategy to maintain productivity while supporting soil, plant, and consumer health. For growers targeting a reduced synthetic input strategy without major yield reduction, the combined application of vermicompost at 30t/ha and foliar amino acids at 3mL/L, applied biweekly for a total of five applications, can be adopted as an integrated nutrient management program, achieving performance comparable to NPK fertilization for several yield and quality traits. Regular monitoring of plant nutritional status is recommended to ensure balanced mineral supply and optimal crop performance.

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