International Journal of Agriculture and Biosciences 2026 15(4): 1738-1745.
https://doi.org/10.47278/journal.ijab/2026.086

RESEARCH ARTICLE
eISSN: 2306-3599; pISSN: 2305-6622

Arthrospira platensis (Spirulina) as a Sustainable Biofertilizer: Influence on Radish Growth and Seed Germination

Josue Duarte, Rafael Lazo, Miguel A. Reinoso, Denny Moreno and Diego Barzallo*

Universidad Estatal de Milagro, Milagro, Provincia del Guayas, Ecuador, 091050
*Corresponding author: dbarzallog@unemi.edu.ec

ABSTRACT

This study assessed the effect of *Arthrospira* (Spirulina) *platensis* as a biofertilizer on the germination and development of *Raphanus sativus* (radish). A semi-open photobioreactor with Zarrouk medium was employed for the cultivation of the cyanobacterium. The temperature was maintained at 32°C using a heater, and aeration was controlled through a 6/30 pumping cycle to ensure proper gas exchange. A 12-hour light/12-hour dark photoperiod was used with artificial fluorescent light. After harvesting, different biofertilizer formulations were prepared from dry biomass and cultures in the exponential phase, which were compared with a commercial fertilizer and a control treatment. Variables such as germination rate, number of leaves, stem height, leaf width, and survival rate were analyzed. The results showed that treatments with spirulina improved the germination rate, with treatments T2 and T4 showing the best results. Moreover, during the growth stage, these treatments significantly increased stem height, leaf number, and survival rate compared with the commercial fertilizer. Statistical analysis using ANOVA, Tukey's test, and principal component analysis (PCA) confirmed significant differences between the treatments, supporting the effectiveness of the microalga-based biofertilizer as an alternative to conventional fertilizers, demonstrating its potential as a natural biostimulant.

Keywords: Biofertilizer, Biostimulant, Plant growth, *Arthrospira platensis, Raphanus Sativus*.

Article History
Article # 25-473
Received: 15-Aug-25
Revised: 28-Sep-25
Accepted: 14-Dec-25
Online First: 05-Apr-26

INTRODUCTION

The excessive use of chemical fertilizers in agriculture negatively impacts soil health and the environment. It disrupts soil microbiota, reduces biodiversity, and hinders essential processes like organic matter decomposition and nutrient cycling (Singh, 2018). Prolonged use depletes soil organic matter, harms beneficial microorganisms, reduces water retention, and contributes to erosion and desertification (Tripathi et al., 2020). Although synthetic fertilizers increase crop yields, they cause water contamination, long-term soil degradation, and high costs for farmers, ultimately causing a decline in soil fertility (Jáquez et al., 2022).

There is a growing need to develop biofertilizers as a sustainable alternative to enhance agricultural productivity without compromising soil composition. One of the key advantages of organic biofertilizers is their ability to release essential nutrients into the soil. Furthermore, they stimulate the activity of beneficial bacteria and fungi, which improve nutrient uptake and promote plant growth (Prisa & Spagnuolo, 2023). For example, biofertilizers based on *Rhizobium* or *Azospirillum* increase moisture retention and promote beneficial microorganisms, which enhance nutrient availability and plant growth (Mamani, 2023).

On the other hand, the development of biofertilizers derived from microalgae is increasingly recognized as a sustainable alternative to reduce the use of chemicals in modern agriculture. *Arthrospira platensis* (cyanobacterium, commonly referred to as Spirulina) is known for improving nutrient supply/availability and plant vigor in a sustainable way (El Shazoly et al., 2024). *Arthrospira platensis* is characterized by its high protein content (50%–70%), essential amino acids, and bioactive compounds, which contribute to enhanced plant growth and soil health (Gonçalves et al., 2023). This cyanobacterium promotes root development, alleviates oxidative stress, and combats pathogens through bioactive components like phycocyanin,

Cite this Article as: Duarte J, Lazo R, Reinoso MA, Moreno D and Barzallo D, 2026. *Arthrospira platensis* (Spirulina) as a sustainable biofertilizer: influence on radish growth and seed germination. International Journal of Agriculture and Biosciences 15(4): 1738-1745. https://doi.org/10.47278/journal.ijab/2026.086

A Publication of Unique Scientific Publishers

known for its antioxidant and anti-inflammatory properties (Barceló et al., 2025). Exopolysaccharides present in *Arthrospira platensis*, enriched with fatty acids and micronutrients such as Fe, Mg, K, and Zn, play a vital role in seed germination, root development, and the regeneration of soil microbiota (Chabili et al., 2024).

Microalgae-based biofertilizers promote plant growth, improve disease resistance, and offer a sustainable alternative to synthetic fertilizers, enhancing soil quality without environmental harm (La Bella et al., 2022; Shoukat, 2025). They convert essential nutrients (N, P, K) into plant-available forms, produce bioactive substances like phytohormones, and encourage beneficial interactions with soil microorganisms, contributing a healthy soil microbiome (Moreira et al., 2022). Studies highlight their potential to enhance soil fertility, increase crop yield, and improve agricultural productivity, supporting sustainable farming practices and enriching crop nutritional value (Wichaphian et al., 2025). In addition, the positive effects of the application of cyanobacteria and other microalgae on seed germination and seedling growth have been consistently reported, which are largely attributable to the presence of exopolysaccharides (EPS) and micronutrients within the biomass. EPS secreted by *Arthrospira platensis* play an important role in improving water retention in the substrate, enhancing nutrient absorption, and providing protection to seedlings against osmotic stress, ultimately contributing to greater vigor and more robust root development (Chaudhuri & Balasubramanian, 2023). Experimental studies have further demonstrated that EPS production increases under optimized culture conditions, allowing the resulting biomass to exhibit a greater capacity to interact with soil nutrients and to confer protection against osmotic stress (Rachidi et al., 2020). Moreover, EPS produced by *Arthrospira platensis* exhibit chemical properties that support the formation of stronger cellular structures and the modulation of plant metabolic processes, increasing tolerance to abiotic stress (Laroche, 2022). In this way, EPS derived from *Arthrospira platensis* can be considered an effective strategy to promote healthier and more sustainable growth practices in agriculture. Furthermore, fresh biomass of *Arthrospira platensis* contains auxin precursors, such as tryptophan, which are involved in the modulation of plant hormonal pathways and contribute to processes including root initiation and cell division (Santini et al., 2021). A recent study reported that *Arthrospira platensis* can secrete biopolymers that act as elicitors, triggering signaling cascades which modulate gene expression related to hormone biosynthesis and preparing plants for improved growth and stress tolerance (Osathanunkul et al., 2025). Likewise, antioxidant compounds naturally present in *Arthrospira platensis*, such as phycocyanin, carotenoids, and specific enzymes, contribute to mitigating abiotic stress by neutralizing reactive oxygen species (ROS) generated by drought, salinity, or excessive light, thus protecting the structural and functional integrity of plant cells (Heydarnajad et al., 2024). Therefore, these bioactive compounds highlight the potential of *Arthrospira platensis* as a comprehensive biostimulant, capable of promoting plant growth, facilitating nutrient uptake, and enhancing tolerance to a wide range of agronomic challenges.

Radish (*Raphanus sativus*) is a valuable crop known for its short growth cycle, nutritional value, and climate adaptability. However, challenges like low soil nutrients, environmental factors, drought, and agrochemical pollution can limit its growth. Thus, innovative strategies are needed to enhance production (Kanjevac et al., 2022). Microalgae-based biofertilizers, such as *Arthrospira platensis*, offer a sustainable alternative to improve soil fertility, stimulate root growth, enhance mineral absorption, boost plant resistance, and increase yield (Xu et al., 2023). Currently, previous research reports have shown that extracts and biomass from cyanobacteria have beneficial effects on seed germination and early seedling development in different agricultural crops. For example, aqueous applications of *Spirulina platensis* significantly improve growth rate, vigor, and robustness in tomato seedlings (Pratiwi et al., 2025). Similarly, proteins such as phycocyanin extracted from *Spirulina platensis* enhance germination and stimulate biochemical processes in tomato seeds, while aqueous extracts applied at high concentrations have been reported to increase wheat germination from 88.9% to 97.8%, also improving seedling vigor (Hamouda et al., 2022). Other studies with different microalgae have also found improvements in lettuce germination, root development, and the accumulation of bioactive compounds such as sugars, polyphenols, and chlorophyll (Metwally et al., 2022). As can be noted, most previous studies on *Arthrospira platensis* and other microalgal biostimulants have focused on long-cycle or high-value crops, mainly through foliar application, whereas research on short-cycle vegetables such as *Raphanus sativus* remains limited.

Thus, this study aims to develop an organic biofertilizer based on Arthrospira platensis and to evaluate its effect on radish seed germination and seedling growth by testing two delivery modes (fully solubilized dry biomass and exponential phase culture) and by comparing them with an unfertilized control and a commercial fertilizer. The results demonstrate its effectiveness in enhancing soil fertility, nutrient absorption, and plant resistance, supporting the potential of spirulina as a biofertilizer in sustainable agriculture.

MATERIALS & METHODS

Location

The research was conducted in Babahoyo, Los Ríos Province, Ecuador (1°48'47.0"S, 79°30'24.5"W). An experimental plot of 5m² was established, with a planting distance of 15cm between plants to ensure adequate distribution and uniform growth. The regional climatic conditions during the study included an average temperature of 28°C and a relative humidity of 80%. The experiment was carried out in 1L pots, each containing 1.2kg of moist substrate. The substrate was previously characterized by the National Institute of Agricultural Research (INIAP), and its physicochemical composition is presented in Table 1. Irrigation was applied every two days, with a dose of 100mL of water per plant, equivalent to approximately 300mL per week. This regime was maintained throughout the 24-day evaluation period, totaling 12 irrigation events per plant.

Table 1: Physicochemical properties of the substrate

Parameters	Units	Reading
pH		5.20
OM	%	6.40
N	mg kg^{-1}	38.0
K	mg kg^{-1}	80.0
Ca	mg kg^{-1}	619.0
Mg	mg kg^{-1}	107.0
P	mg kg^{-1}	4.0
Zn	mg kg^{-1}	1.4
Cu	mg kg^{-1}	8.7
Fe	mg kg^{-1}	151.0
Mn	mg kg^{-1}	11.0
S	mg kg^{-1}	1.4
B	mg kg^{-1}	0.22

Experimental Design

The experiment was performed under a completely randomized design (CRD) with six treatments. The first treatment corresponded to the control with water (T1), followed by the application of the biofertilizer based on *Arthrospira platensis* in two forms: dry biomass (T2 and T3) and solubilized biomass (T4 and T5), and finally a treatment with the commercial fertilizer BIO Ca-B-Zn (T6), as detailed in Table 2. Each treatment included eight replicates, for an initial total of 48 radish seeds. The experimental unit was each individual seed, which was established in its own pot with previously characterized substrate. Randomization was performed by independently and randomly assigning seeds to each treatment to avoid positional bias. During the germination phase, the seeds were maintained under controlled conditions and subsequently transplanted into the experimental substrate while preserving the initial random distribution. At the end of the three-week evaluation period, partial mortality was recorded, resulting in a total of 33 viable individuals (n = 33), which were considered in the statistical analysis.

Table 2: Number of replications in the different treatments with A. platensis application

Treatment	Applied concentration
T1 (Control)	100mL of distilled water
T2 (Dry biomass) *	1g kg^{-1},100mL per pot
T3 (Dry biomass) *	0.5g kg^{-1},100mL per pot
T4 (Exponential-phase culture)	OD_{750} ≈1.15,100mL per pot
T5 (Exponential-phase culture)	OD_{750} ≈ 0.21,100mL per pot
T6 (Commercial fertilizer)	100mL(manufacturer's dose)

*Dry biomass in T2 and T3 was fully solubilized before application. OD_{750}: Optical Density at 750 nm. In each treatment, there were 8 replicates.

Preparation of Biofertilizer from *Arthrospira platensis* (Spirulina)

The *Arthrospira platensis* strain was obtained from the company Biotechplant and used as the base for biofertilizer production. An initial culture volume of 1 liter was scaled up in a semi-open photobioreactor to ensure optimal growth and biomass production conditions. Zarrouk medium was used for spirulina cultivation, which contains a balanced concentration of essential macro and micronutrients that promote the growth of spirulina (Delrue et al., 2017). Additionally, a continuous feeding system was implemented every 2 days to ensure a constant renewal of nutrients and proper maintenance of biomass in the reactor. To enhance growth, the temperature was maintained at 32°C using a heater, and an aeration system was installed with a pressure of 0.012MPa and a total flow rate of 6L min^{-1} (two diffusers of 3L min^{-1} each). The aeration system operated in six cycles of 30 minutes each during the photoperiod, ensuring proper mixing and oxygen availability. Illumination was provided by fluorescent LED lamps with an intensity of 153µmol m^{-2} s^{-1}, under a photoperiod of 12h light/12h dark controlled by a timer to simulate a diurnal cycle.

Once an optimal biomass concentration was achieved, the culture was harvested and the biomass was dried at 60°C for 7 hours in a dehydrator to reduce moisture content and preserve bioactive compounds such as proteins, essential amino acids, pigments, and secondary metabolites with potential biostimulant effects (Ryndin et al., 2023). Subsequently, a characterization of macronutrients and micronutrients in the dried biomass was conducted at the INIAP.

For the preparation of the biofertilizer, four experimental treatments and one control treatment (T1) were established to evaluate the impact of spirulina on the germination and seedling growth of radish. In treatment T2, a solution was prepared by dissolving 1g of dried biomass in 1L of distilled water, while T3 used a lower concentration, with 0.5g of dried biomass in 1 liter of distilled water. Treatment T4 involved applying 100mL of culture in the exponential growth phase directly from the photobioreactor, T5 utilized 100mL of culture in the exponential phase diluted to 10%, and T6 employed a commercial fertilizer BIO Ca-B-Zn (AGRITEC, Ecuador), whose composition is shown in Table 3.

Table 3: Composition of commercial fertilizer

Parameters	Units	Reading
N	%	7
Ca	%	15
Zn	%	4
B	%	2
Free amino acids	%	4.9
Acid fulvic	%	4.5

Biofertilizer Application and Evaluation Parameters

To assess the impact of the spirulina-based biofertilizer, eight radish seeds were used for each treatment and subjected to an initial germination phase in a controlled environment. Germination was carried out using the cotton test in a sealed container, where each seed received 20 mL of the solution corresponding to its respective treatment. The germination process was monitored over a three-day period (Sinyavina et al., 2023). Once germinated, the seedlings were transplanted to the substrate, where their physiological development was assessed under the application of the different treatments. The parameters considered for the growth analysis included germination, number of leaves, stem height (cm), leaf width (cm), and survival rate (%) over time.

Following germination, the seedlings were transplanted into the substrate, and their physiological development was evaluated under the application of the different treatments. The growth parameters considered for analysis included germination rate, leaf count, stem height, leaf width, and survival rate over time. Growth evaluation was conducted continuously over 24 days, with the biofertilizer applied every seven days. Each seedling received 100mL of the treatment solution throughout the experiment. Therefore, measurements were taken at 24 days of each growth parameter, enabling an assessment of the biofertilizer effect on radish physiology and its potential as a sustainable alternative to conventional fertilizers.

In any case, the Spirulina-based biofertilizer treatments influence plant growth through the availability of macronutrients and micronutrients. Nitrogen plays a pivotal role in leaf formation and chlorophyll synthesis, promoting photosynthesis and seedling growth. Phosphorus supports root development and ATP synthesis during germination, while potassium enhances survival rates by improving water and nutrient transport, drought tolerance, and leaf width (Balestri & Podgórska, 2024). Calcium strengthens stem integrity, supporting growth and stability (Bayona et al., 2020). Additionally, the dry biomass of spirulina serves as a sustainable protein source, reinforcing its role as a bio-stimulant, thus enhancing radish physiology from germination to full development (Prisa et al., 2023).

Statistical Analysis

The data obtained throughout the experiment were subjected to statistical analysis to evaluate the impact of the biofertilizer. A one-way analysis of variance (ANOVA) was conducted to assess significant differences between treatments for each variable. The assumptions of normality and homoscedasticity were evaluated using the Shapiro–Wilk and Levene tests, respectively. The Shapiro–Wilk test indicated that the residuals did not follow a normal distribution for most variables, while the nonparametric Kruskal–Wallis test was also performed to provide a robust evaluation of treatment effects. In cases where significant differences were detected, a Tukey multiple comparison test was applied with a significance level of $\alpha=0.05$ to identify which treatments exhibited statistically distinct effects. Furthermore, the statistical analysis was complemented by principal component analysis (PCA). All analyses were performed using R Studio software to visualize the behavior of the evaluated variables and assess the biofertilizer impact on crop development. A schematic representation of the entire process implemented in the study is provided in Fig. 1.

RESULTS AND DISCUSSION

Characterization of Spirulina-based Biofertilizer

The characterization of the biofertilizer included the analysis of macronutrients and micronutrients, as shown in Table 4. The findings indicate that the macronutrient content in the biofertilizer positively influences plant development. Notably, nitrogen, with a concentration of 10%, plays a crucial role in protein formation and vegetative growth, positively influencing leaf number and stem height. Phosphorus (9.21g L^{-1}) is crucial for root development, enhancing germination and nutrient absorption, leading to better crop yield (Balestri & Podgórska, 2024).

Table 4: Characterization of macronutrients and micronutrients in dry biomass

Parameters	Units	Reading
N	%	10
P	mg kg^{-1}	9212
K	mg kg^{-1}	1581
Ca	mg kg^{-1}	5076
Mg	mg kg^{-1}	4758
Cu	mg kg^{-1}	7
Fe	mg kg^{-1}	1347
Mn	mg kg^{-1}	31
Zn	mg kg^{-1}	15

Furthermore, the biofertilizer demonstrated a well-balanced composition of micronutrients, including essential elements such as Ca, Mg, Cu, Fe, Mn, and Zn, which are crucial for various metabolic processes in plants, particularly in the formation of proteins involved in photosynthesis and electron transport. Their presence enhances plant survival and overall growth (Aghamirzaei et al., 2024). In addition, these micronutrients play a significant role in promoting efficient plant development, particularly during critical stages such as germination and leaf formation, ultimately improving plant performance.

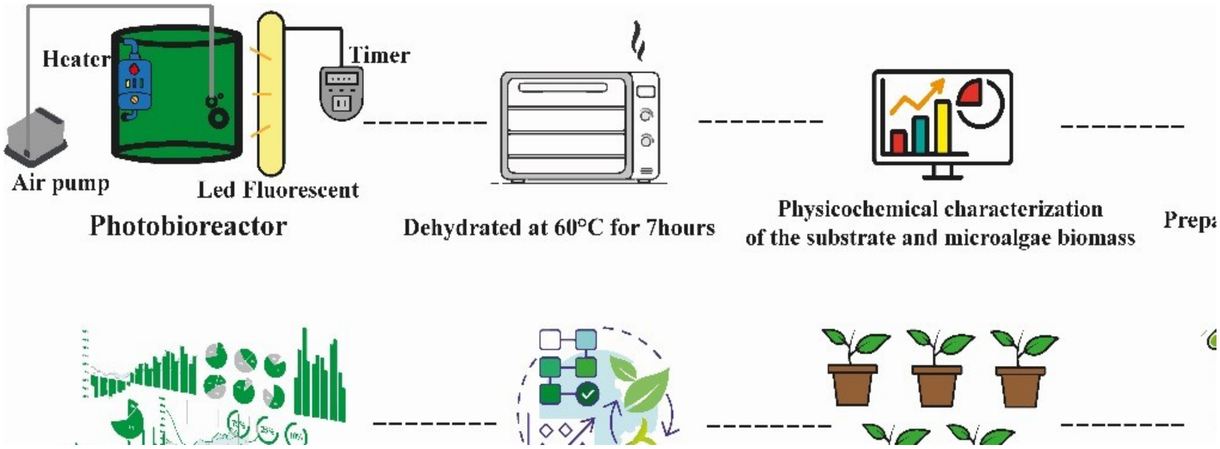

Fig. 1: Schematic representation of the experimental workflow. *Arthrospira platensis* was cultivated in a photobioreactor and used as a biofertilizer applied to radish seeds. Subsequent stages included transplantation, growth assessment, and statistical analysis.

Evaluation of Treatments during the Germination Stage

Radish (*Raphanus sativus*) germination was evaluated under different treatments, revealing differences in germination speed. Each treatment included eight replicates, with the individual seed as the experimental unit, established in its own pot and irrigated with 20 mL of the corresponding solution. Germination was monitored for three days. On day 1, treatments T2 and T4 showed the highest number of germinated seeds. By day 2, T4 had reached almost complete germination, whereas by day 3 all treatments exhibited full germination. Although the final germination percentage was consistent across treatments, differences were reflected in the rate of germination, as indicated by the T_{50} value calculated for each treatment. As shown in Table 5, treatments with the biofertilizer accelerated seed germination compared with the control (T1), highlighting a positive effect on the earliness of initial plant development.

Table 5: Germination of radish seeds after 3 days

Treatment	D1	D2	D3	T_{50}
T1	3	5	8	1.5
T2	6	7	8	0.83
T3	5	7	8	0.5
T4	6	8	8	0.8
T5	5	6	8	0.5
T6	5	7	8	0.5

As shown in Fig. 2, treatments T2 and T4 positively influenced seed germination, likely due to the bioactive compounds and nutrients that promote the metabolic activation of the seeds, demonstrating the potential of spirulina as a bio-stimulant.

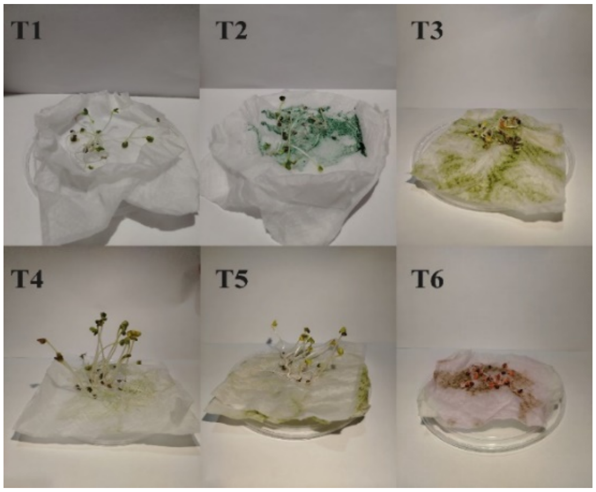

Fig. 2: Germination of radish seeds under six treatments: T1 (control, distilled water), T2–T3 (dry biomass of A. platensis), T4–T5 (exponential-phase cultures of A. platensis), and T6 (commercial fertilizer).

Evaluation of the Studied Variables

To evaluate the effect of *Arthrospira platensis*-based biofertilizer treatments on radish growth, analysis of variance (ANOVA) was performed and the assumptions of normality and homoscedasticity were tested. The Shapiro–Wilk test indicated that the residuals did not follow a normal distribution: number of leaves (W=0.94383, P=1.539e-05), stem height (W=0.95851, p =0.0002485), leaf width (W=0.89517, P=1.208e-08), and survival (W=0.58148, p< 2.2e-16). In contrast, Levene's test showed that variances were homogeneous across treatments for all evaluated variables: number of leaves (F=0.2816, P=0.9225), stem height (F =1.0176, P=0.4098), leaf width (F=0.3021, P=0.9109), and survival (F=0.66, P=0.6544).

Because to the normality assumption was not satisfied, the nonparametric Kruskal–Wallis test was performed alongside ANOVA to provide a robust evaluation of treatment effects. The results showed that the treatments significantly influenced the growth variables (Table 6). ANOVA detected significant differences in number of leaves (F=3.363, df=5, P=0.00674), stem height (F =3.26, df=5, P=0.00818), and leaf width (F=4.408, df=5, P=0.000936). Similarly, the Kruskal–Wallis test identified significant differences for number of leaves (χ^2=17.316, df=5, P=0.00394), stem height (χ^2=14.721, df=5, P=0.0116), and leaf width (χ^2=30.27, df=5, P=1.305e−05).

Table 6: Results of ANOVA and Kruskal–Wallis tests for growth variables in radish under different biofertilizer treatments

Variable	ANOVA F	df	P value	Kruskal-Wallis χ^2	df	P value
Number of leaves	3.363	5	0.00674	17.316	5	0.00394
Stem height (cm)	3.26	5	0.00818	14.721	5	0.0116
Leaf width (cm)	4.408	5	0.000936	30.27	5	1.305e-05

Table 7 summarizes the evaluation of the variables for the treatments applied to radish, highlighting significant differences in leaf number, stem height, leaf width, and survival rate. Treatment T4 exhibited the highest leaf number, followed by T2, with significant differences observed compared to the control (P=0.00674). Tukey's test further revealed significant differences between T4 and T1 (P=0.0016). In terms of stem height, T4 also significantly outperformed all other treatments (P=0.00818). Conversely, T6 showed more moderate growth, with no significant differences in most variables. These findings suggest that the spirulina-based biofertilizer is more effective than commercial fertilizers in enhancing seed germination and promoting plant growth.

In addition, a Principal Component Analysis (PCA) was conducted to reduce data dimensionality and visualize variability among treatments at the level of individual replicates, using stem height, leaf number, leaf width, and survival of each plant as variables. PC1 accounted for 82.4% of the total variance and PC2 for 10.4%, together explaining 92.8% of the variability in the dataset. Fig. 3 shows that treatments with *Arthrospira platensis*-based biofertilizer are clearly separated from the control and commercial fertilizers, indicating a positive effect on radish growth, as reflected by higher values of leaf number, stem height, and leaf width. Conversely, treatments with commercial fertilizers clustered in a region of lower performance and reduced dispersion, reflecting a more limited physiological response in plants.

Table 7: Evaluation of variables after applying spirulina-based biofertilizer and commercial fertilizer

Variables	Treatment					
	T1	T2	T3	T4	T5	T6
Number of leaves	1.17 ± 0.25^{d}	1.79 ± 0.30^{c}	1.62 ± 0.28^{c}	2.21 ± 0.32 ^{a}	1.58 ± 0.32^{c}	1.54 ± 0.28^{c}
Stem height (cm)	2.22 ± 0.40^{d}	3.78 ± 0.42^{c}	3.48 ± 0.41^{c}	9.59 ± 0.60^{a}	2.76 ± 0.38^{d}	2.83 ± 0.39^{d}
Leaf width (cm)	0.65 ± 0.12^{d}	1.10 ± 0.15^{b}	1.03 ± 0.14^{bc}	1.25 ± 0.18^{a}	0.88 ± 0.13 ^{c}	0.98 ± 0.14^{bc}
Survival rate (%)	50 ± 10^{d}	75 ± 8^{b}	75 ± 7^{b}	88 ± 5^{a}	63 ± 9^{c}	63 ± 9^{c}

The measurements for all variables were taken at 24 days. Different letters within each row indicate significant differences according to Tukey's test (α = 0.05).

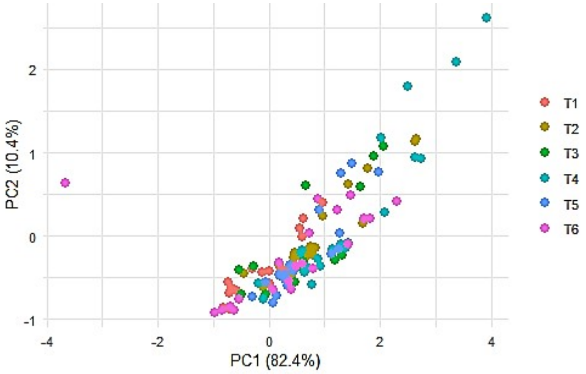

Fig. 3: Principal Component Analysis (PCA) of radish growth variables (stem height, leaf number, leaf width, and survival) under different biofertilizer treatments.

Fig. 4 shows the distribution of values for each variable under different treatments. In stem height (Fig. 4a), the spirulina-based biofertilizer (T4) outperformed the control (T1) and commercial fertilizer (T6). Similarly, for leaf width (Fig. 4b), biofertilizer treatments (T4 and T2) showed better results than T1, suggesting more favorable leaf development. In leaf number (Fig. 4c), T4 had the highest value, followed by T2, confirming the biofertilizer's effectiveness in promoting vegetative growth. T6 showed no significant improvements over the control. These results highlight that the biofertilizer based on *Arthrospira platensis* enhances radish growth compared to both the control and commercial fertilizer, demonstrating its potential as a natural bio-stimulant.

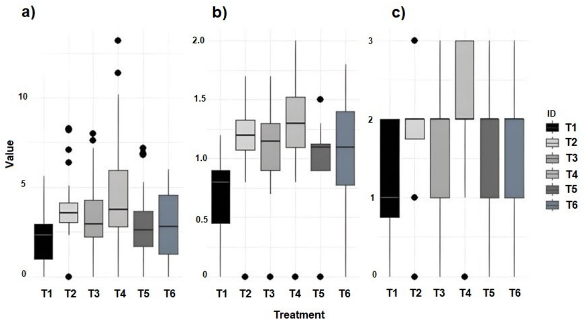

Fig. 4: Box plots of growth parameters of radish seedlings under different treatments (T1–T6): (a) root length, (b) shoot length, and (c) number of leaves. Boxes represent medians and interquartile ranges, whiskers show variability, and dots indicate outliers.

Thus, the positive impact of spirulina as a biofertilizer may be attributed to its composition of essential macro and micronutrients, which play a crucial role in promoting plant development. In this way, Shedeed et al., (2022) found that spirulina extract acted as a growth promoter in *Lupinus luteus*, reinforcing the potential of microalgae as biofertilizers across different crops. Finally, Salvi et al. (2020) reported that spirulina positively influenced the physiology of *Vitis vinifera*, enhancing antioxidant capacity and crop quality. These findings further support the application of this microalga to promote plant development and improve nutrient content in radish cultivation.

Regarding the limitations of this study, it is important to note that the number of replicates was relatively small and that the experiment was conducted on a single species (*Raphanus sativus*) at a single site. These conditions restrict the extrapolation of the results to other crops or agroecological contexts. Nevertheless, from a practical perspective, the *Arthrospira platensis*-based biofertilizer shows strong potential as a sustainable, efficient, and accessible tool for growers, particularly those working in small- and medium-scale systems. In particular, the application of fresh culture at an OD_{750} ≈ 1.15 (T4) emerged as the most effective strategy, suggesting that the exponential phase of the microalgal culture directly influences its performance as a biofertilizer. This opens the possibility for small- and medium-scale farmers to consider cyanobacteria as an alternative input that is both sustainable and potentially more cost-effective compared to synthetic fertilizers. To advance toward field adoption, further trials are needed across different crops, soil conditions, and a cost–benefit analysis that considers local spirulina production, application frequency, and direct comparisons with conventional inputs.

Conclusion

This study demonstrates that spirulina significantly enhances radish germination and growth compared to commercial fertilizers. Treatments with dry biomass and exponential-phase cultures promoted stronger seedlings, with higher stem height, more leaves, and better survival rates. These results suggest that the bioactive compounds and nutrients in radish play a key role in plant growth, supporting its potential as a bio-stimulant for optimal development.

DECLARATIONS

Funding: This work was funded by the Universidad Estatal de Milagro (UNEMI).

Acknowledgment: The authors acknowledge the support and assistance provided by the University Estatal of Milagro (UNEMI)

Conflict of Interest: All authors declare no conflicts of interest.

Data Availability: All the data is available in the article.

Ethics Statement: This study did not require ethical approval, as it did not involve human participants, sensitive personal data, or animal subjects.

Author's Contribution: Diego Barzallo and Miguel A. Reinoso designed the research and conducted the data analysis, Josue Duarte, Diego Barzallo and Rafael Lazo performed the field trials. Denny Moreno and Diego Barzallo reviewed and interpreted the results. All authors contributed to manuscript preparation and final review, approved the final manuscript for submission.

Generative AI Statement: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

Publisher's Note: All claims stated in this article are exclusively those of the authors and do not necessarily represent those of their affiliated organizations or those of the publisher, the editors, and the reviewers. Any product that may be evaluated/assessed in this article or claimed by its manufacturer is not guaranteed or endorsed by the publisher/editors.

REFERENCES

Aghamirzaei, H., Mumivand, H., Nia, A.E., Raji, M.R., Maroyi, A., & Maggi, F. (2024). Effects of Micronutrients on the Growth and Phytochemical Composition of Basil (Ocimum basilicum L.) in the Field and Greenhouse (Hydroponics and Soil Culture). *Plants*, *13*(17), 2498. https://doi.org/10.3390/PLANTS13172498/S1

Balestri, F., & Podgórska, I. (2024). Spirulina—An Invaluable Source of Macro- and Micronutrients with Broad Biological Activity and Application Potential. *Molecules*, *29*(22), 5387. https://doi.org/10.3390/MOLECULES29225387

Barceló, J., Fiorentino, S., Bellani, L., Santin, M., Castagna, A., Echeverria, M. C., & Giorgetti, L. (2025). Effects of Microalgae as Biostimulants on Plant Growth, Content of Antioxidant Molecules and Total Antioxidant Capacity in Chenopodium quinoa Exposed to Salt Stress. *Plants*, *14*(5), 781. https://doi.org/10.3390/PLANTS14050781

Bayona, P.J., Plaza, B.M., Gómez, S.C., Rojas, E., & Jiménez, B.S. (2020). Effect of the foliar application of cyanobacterial hydrolysate (Arthrospira platensis) on the growth of Petunia x hybrida under salinity conditions. *Journal of Applied Phycology*, *32*(6), 4003–4011. https://doi.org/10.1007/s10811-020-02192-3

Chabili, A., Minaoui, F., Hakkoum, Z., Douma, M., Meddich, A., & Loudiki, M. (2024). A Comprehensive Review of Microalgae and Cyanobacteria-Based Biostimulants for Agriculture Uses. *Plants*, *13*(2), 159. https://doi.org/10.3390/PLANTS13020159

Chaudhuri, R., & Balasubramanian, P. (2023). Evaluating the potential of exopolysaccharide extracted from the spent cultivation media of Spirulina sp. as plant biostimulant. *Biomass Conversion and Biorefinery, 48, 658*. https://doi.org/10.1007/S13399-023-04865-8

Delrue, F., Alaux, E., Moudjaoui, L., Gaignard, C., Fleury, G., Perilhou, A., Richaud, P., Petitjean, M., & Sassi, J.F. (2017). Optimization of Arthrospira platensis (Spirulina) Growth: From Laboratory Scale to Pilot Scale. *Fermentation*, *3*(4), 59. https://doi.org/10.3390/FERMENTATION3040059

El Shazoly, R.M., Aloufi, A.S., & Fawzy, M.A. (2024). The Potential Use of Arthrospira (Spirulina platensis) as a Biostimulant for Drought Tolerance in Wheat (Triticum aestivum L.) for Sustainable Agriculture. *Journal of Plant Growth Regulation*, *44*(2), 686–703. https://doi.org/10.1007/s00344-024-11473-x

Gonçalves, J., Freitas, J., Fernandes, I., & Silva, P. (2023). Microalgae as Biofertilizers: A Sustainable Way to Improve Soil Fertility and Plant Growth. *Sustainability*, *15*(16), 12413. https://doi.org/10.3390/SU151612413

Hamouda, R.A., Shehawy, M.A., Mohy El Din, S.M., Albalwe, F.M., Albalawi, H. M.R., & Hussein, M.H. (2022). Protective role of Spirulina platensis liquid extract against salinity stress effects on Triticum aestivum L. *Green Processing and Synthesis*, *11*(1), 648–658. https://doi.org/10.1515/gps-2022-0065

Heydarnajad, R., Torabi Giglou, M., Hatami, M., & Ghorbanpour, M. (2024). Potential of natural stimulants and spirulina algae extracts on Cape gooseberry plant: A study on functional properties and enzymatic activity. *Food Science & Nutrition*, *12*(11), 9056. https://doi.org/10.1002/FSN3.4342

Jáquez, S.V.M., Pérez, S.G., Márquez, L.M., & Pérez, V.G. (2022). Impactos económicos y ambientales de los plaguicidas en cultivos de maíz, alfalfa y nogal en durango, México. *Revista Internacional de Contaminación Ambiental*, *38*, 219–233. https://doi.org/10.20937/RICA.54169

Kanjevac, M., Jakovljević, D., Todorović, M., Stanković, M., Ćurčić, S., & Bojović, B. (2022). Improvement of Germination and Early Growth of Radish (Raphanus sativus L.) through Modulation of Seed Metabolic Processes. *Plants*, *11*(6), 757. https://doi.org/10.3390/PLANTS11060757

La Bella, E., Baglieri, A., Fragalà, F., & Puglisi, I. (2022). Multipurpose Agricultural Reuse of Microalgae Biomasses Employed for the Treatment of Urban Wastewater. *Agronomy*, *12*(2), 234. https://doi.org/10.3390/AGRONOMY12020234

Laroche, C. (2022). Exopolysaccharides from Microalgae and Cyanobacteria: Diversity of Strains, Production Strategies, and Applications. *Marine Drugs*, *20*(5), 336. https://doi.org/10.3390/MD20050336

Mamani, A. (2023). Biofertilizantes a base de microorganismos beneficiosos y materia orgánica: una revisión sistemática. *Revista Acciones Médicas*, *2*(4), 43–55. https://doi.org/10.35622/j.ram.2023.04.004

Metwally, R.A., Abdelhameed, R.E., Soliman, S.A., & Al-Badwy, A.H. (2022). Potential use of beneficial fungal microorganisms and C-phycocyanin extract for enhancing seed germination, seedling growth and biochemical traits of Solanum lycopersicum L. *BMC Microbiology*, *22*(1), 1–17. https://doi.org/10.1186/s12866-022-02509-x

Moreira, J.B., Vaz, B.daS., Cardias, B.B., Cruz, C.G., Almeida, A.C.A. de, Costa, J.A.V., & Morais, M.G.de. (2022). Microalgae Polysaccharides: An Alternative Source for Food Production and Sustainable Agriculture. *Polysaccharides*, *3*(2), 441–457. https://doi.org/10.3390/POLYSACCHARIDES3020027

Osathanunkul, M., Thanaporn, S., Karapetsi, L., Nteve, G. M., Pratsinakis, E., Stefanidou, E., Lagiotis, G., Avramidou, E., Zorxzobokou, L., Tsintzou, G., Athanasiou, A., Mpelai, S., Constandinidis, C., Pantiora, P., Merino, M., Mullor, J. L., Dobrovic, L., Cerasino, L., Ogawa, T., Tsaousi, M., Rodrigues, A. M. C., Cardoso, H., Pires, R., Figueiredo, D., Inês F. Costa, I. F., Anjos, C., Labrou, N. E., Madesis, P. (2025). Diversity of Bioactive Compounds in Microalgae: Key Classes and Functional Applications. *Marine drugs*, *23*(6), 222. https://doi.org/10.3390/md23060222

Pratiwi, I.W., Rahmawati, F.A., Samtani, K., Atuilah, N., Hidayatullah, R.A., Alfiah, N.A., Wilujeng, E.D.I., Anindita, D.C., Shidiqi, M.H.A., & Adnan, Moch. R. (2025). Vigor Enhancement of Tomato (Solanum lycopersicum) using Spirulina platensis as Seed Priming Agent. *Biota : Jurnal Ilmiah Ilmu-Ilmu Hayati*, *10*(2), 148–160. https://doi.org/10.24002/BIOTA.V10I2.10220

Prisa, D., Fresco, R., & Spagnuolo, D. (2023). Microbial Biofertilisers in Plant Production and Resistance: A Review. *Agriculture*, *13*(9), 1666. https://doi.org/10.3390/AGRICULTURE13091666

Prisa, D., & Spagnuolo, D. (2023). Plant Production with Microalgal Biostimulants. *Horticulturae*, *9*(7), 829. https://doi.org/10.3390/HORTICULTURAE9070829

Rachidi, F., Benhima, R., Sbabou, L., & El Arroussi, H. (2020). Microalgae polysaccharides bio-stimulating effect on tomato plants: Growth and metabolic distribution. *Biotechnology Reports*, *25*, e00426. https://doi.org/10.1016/J.BTRE.2020.E00426

Ryndin, K.G., Butyrin, A.V., Grigorenko, A.V., Chunzhuk, E.A., Chernova, N.I., Kiseleva, S.V., Malaniy, S.Y., Bakumenko, E.A., Slavkina, O.V., Ossipov, K., Maryutina, T.A., Kumar, V., & Vlaskin, M.S. (2023). From the Cultivation of Arthrospira platensis at an Increased CO2 Concentration to the Bio-Oil Production by Hydrothermal Liquefaction. *Applied Sciences*, *13*(17), 9950. https://doi.org/10.3390/APP13179950

Salvi, L., Niccolai, A., Cataldo, E., Sbraci, S., Paoli, F., Storchi, P., Rodolfi, L., Tredici, M.R., & Mattii, G.B. (2020). Effects of Arthrospira platensis Extract on Physiology and Berry Traits in Vitis vinifera. *Plants*, *9*(12), 1805. https://doi.org/10.3390/PLANTS9121805

Santini, G., Biondi, N., Rodolfi, L., & Tredici, M.R. (2021). Plant Biostimulants from Cyanobacteria: An Emerging Strategy to Improve Yields and Sustainability in Agriculture. *Plants*, *10*(4), 643.

https://doi.org/10.3390/PLANTS10040643

Shedeed, Z.A., Gheda, S., Elsanadily, S., Alharbi, K., & Osman, M.E.H. (2022). Spirulina platensis Biofertilization for Enhancing Growth, Photosynthetic Capacity and Yield of Lupinus luteus. *Agriculture*, *12*(6), 781. https://doi.org/10.3390/AGRICULTURE12060781

Shoukat, A. (2025). Nanofertilizers and stress management: emerging opportunities for climate-resilient farming. *Agrobiological Records, 22,* 73-88. https://doi.org/10.47278/journal.abr/2025.050

Singh, B. (2018). Are Nitrogen Fertilizers Deleterious to Soil Health? *Agronomy*, *8*(4), 48. https://doi.org/10.3390/AGRONOMY8040048

Sinyavina, N.G., Kochetov, A.A., Kocherina, N.V., Egorova, K.V., Kurina, A.B., Panova, G.G., & Chesnokov, Y.V. (2023). Breeding Approaches for Controlled Conditions of Artificial Light Culture for Small Radish and Radish (Raphanus sativus L.). *Horticulturae*, *9*(6), 678. https://doi.org/10.3390/horticulturae9060678

Tripathi, S., Srivastava, P., Devi, R.S., & Bhadouria, R. (2020). Influence of synthetic fertilizers and pesticides on soil health and soil microbiology. *Agrochemicals Detection, Treatment and Remediation: Pesticides and Chemical Fertilizers*, 30, 25–54. https://doi.org/10.1016/B978-0-08-103017-2.00002-7

Wichaphian, A., Kamngoen, A., Pathom-aree, W., Maneechote, W., Khuendee, T., Chromkaew, Y., Cheirsilp, B., Shyu, D.J.H., & Srinuanpan, S. (2025). Integrating Microalgal Chlorella Biomass and Biorefinery Residues into Sustainable Agriculture and Food Production: Insights from Lettuce Cultivation. *Foods*, *14*(5), 808. https://doi.org/10.3390/FOODS14050808

Xu, Q., Zhu, T., Zhao, R., Zhao, Y., Duan, Y., Liu, X., Luan, G., Hu, R., Tang, S., Ma, X., Liu, Y., Li, S., & Lu, X. (2023). Arthrospira promotes plant growth and soil properties under high salinity environments. *Frontiers in Plant Science*, *14*, 1293958. https://doi.org/10.3389/fpls.2023.1293958