Improvement of growth and productivity in potato (*Solanum tuberosum* L.) crop by using biostimulants

Mejora del crecimiento y productividad del cultivo de papa (*Solanum tuberosum* L.) mediante el uso de bioestimulantes

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ABSTRACT

In Colombia, potato cultivation has significant social and economic importance for the population; however, rising input costs and low yields have led to a decline in the areas planted in the country. Biostimulants are substances or microorganisms that can enhance yield by improving the physiological processes of the plants. In Colombia, there are few studies evaluating their efficiency on potato productivity. Therefore, the aim of this research was to assess the effect of biostimulant applications on the growth and productivity of potato (*Solanum tuberosum* L.) variety 'CIP 39' under the conditions of the municipality of Paipa, Boyacá department. A completely randomized design was used, with four treatments corresponding to commercially registered biostimulants with an active hormonal ingredient, seaweed extract (SWE), or carboxylic acids, and a control. Variables such as fresh and dry weight of roots, shoots, and total biomass, leaf area index (LAI), yield by quality, and total yield were evaluated. The application of biostimulants resulted in improved physiological response of the plants. The SWE-based biostimulant exhibited a better balance in terms of fresh and dry biomass, as well as in LAI, leading to a significant increase in quality and yield. This indicates that the application of biostimulants can be an alternative to increase productivity in this production system.

Key words: seaweed extracts, carboxylic acids, plant biostimulation, sustainable production.

RESUMEN

En Colombia el cultivo de papa tiene gran importancia social y económica para la población; sin embargo, el aumento de los precios de los insumos y los bajos rendimientos han generado una caída en las áreas sembradas del país. Los bioestimulantes son sustancias o microorganismos que pueden mejorar el rendimiento, a través de la mejora de los procesos fisiológicos de la planta. En Colombia hay escasos estudios que evalúen la eficiencia de aquellos sobre la productividad en el cultivo de papa; por esto el objetivo de esta investigación fue evaluar el efecto de las aplicaciones de bioestimulantes en el crecimiento y productividad del cultivo de papa (*Solanum tuberosum* L.) variedad 'CIP 39' bajo condiciones del municipio de Paipa, departamento de Boyacá. Se utilizó un diseño completamente al azar, con cuatro tratamientos que correspondieron a bioestimulantes comerciales registrados cuyo compuesto activo fuera de tipo hormonal, extracto de algas marinas (EAM) o ácidos carboxílicos, y un control. Se evaluaron las variables de peso fresco y seco de raíz, parte aérea y total, índice de área foliar (IAF), rendimiento por calidades y total. La aplicación de bioestimulantes resultó en una mejor respuesta fisiológica de la planta. El bioestimulante a base de EAM mostró un mejor balance en cuanto a la biomasa fresca y seca, así como en el IAF; esto generó un aumento significativo de la calidad y el rendimiento. Esto indica que la aplicación de bioestimulantes puede ser una alternativa para aumentar la productividad en este sistema productivo.

Palabras clave: extractos de algas marinas, ácidos carboxílicos, bioestimulación de plantas, producción sostenible.

Introduction

The potato (*Solanum tuberosum* L.) is one of the most important crops worldwide for both human consumption and industrial use (Sebnie *et al.*, 2021). It is considered a versatile food with high nutritional and energetic value due to its high content of starch and antioxidants such as polyphenols, amino acids, essential minerals, and vitamins B6, B3, and C (Van Dingenen *et al.*, 2019).

The potato supply chain in Colombia generates approximately 264,000 jobs annually, of which around 75,000 are direct jobs and about 189,000 are indirect. Annual variations are due to changes in the planted area. It is estimated that potato cultivation alone generates around 20 million workdays per year, with nearly 100,000 families dedicated to potato farming across 9 departments and 283 municipalities (Vélez, 2020). However, the high cost of agricultural inputs, along with the low response of crops

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to fertilization (Hailu *et al*., 2017), has increased interest in the development of technologies and practices that improve agricultural efficiency and productivity (Torres-Hernández *et al*., 2023). Among these, the application of biostimulants is becoming a sustainable agricultural practice with positive effects on crop yields (Brown & Saa, 2015).

Currently, the production of sustainable crops is focused on obtaining high-value products, where biostimulants have been gaining increasing importance (Bulgari *et al*., 2019). According to du Jardin (2015), a plant biostimulant is any substance or microorganism applied to plants with the aim of enhancing nutrient efficiency, abiotic stress tolerance, and/or crop quality traits, regardless of its nutrient content. These substances are not considered mineral nutrients but facilitate nutrient uptake or beneficially contribute to growth promotion and tolerance to abiotic and biotic stress (Brown & Saa, 2015). Biostimulants can be classified as humic substances (humic and fulvic acids), protein hydrolysates (peptides and free amino acids (FAAs)), seaweed extracts and botanicals, chitosan and other biopolymers, inorganic compounds (beneficial and essential mineral elements), beneficial fungi and bacteria (du Jardin, 2015).

According to Li *et al*. (2022), plant biostimulants are products that stimulate plant growth, improve nutrient use efficiency, enhance abiotic stress tolerance, improve crop quality, and increase the availability of nutrients in the soil or plant rhizosphere. This is achieved by inducing both structural and physiological changes in plants related to nutrient absorption, assimilation, and distribution, as well as changes in the primary and secondary metabolism of the plants (Canellas & Olivares, 2014). Consequently, vegetable, cereal, and ornamental crops exhibit greater vigor, higher yields, and improved harvest quality (Kisvarga *et al*., 2022). Plant biostimulants can be applied either through soil (edaphically) or by foliar application, promoting positive effects on plant growth, nutrition, and quality traits in crops (Van Oosten *et al*., 2017).

Research conducted on crops such as beans (Martínez *et al*., 2017), soybeans (Santos *et al*., 2017), maize (Lephatsi *et al*., 2022), and potatoes (Lazzarini *et al*., 2022; Wadas & Dziugieł, 2020) in other countries indicated that biostimulants can improve nutritional efficiency, tolerance to abiotic stress, and crop quality. In Colombia, the use of biostimulants has been increasing substantially; however, there are few studies evaluating the effect of biostimulants on the productivity of crops such as potatoes, which are of great social and economic importance to the country.

According to the above, various studies indicate the beneficial effects of using biostimulants. However, research on the use of these types of products in Colombia is limited, particularly for species where the organ of commercial interest is roots or tubers. This study was conducted to understand the response of potato (*Solanum tuberosum* L.) plants variety CIP 39 in terms of growth, biomass gain, and productivity when subjected to the application of different types of biostimulants during their growth under field conditions.

Materials and methods

Location

The research was conducted at the Tunguavita Experimental Farm of the Pedagogical and Technological University of Colombia (UPTC) located in the municipality of Paipa (Boyacá, Colombia) in the Salitre district. The geographical coordinates are 5°45' N and 73°45' W at an altitude of 2470 m a.s.l. The site has an average annual temperature of 14.1°C, a bimodal rainfall pattern with an average annual precipitation of 966 mm, and a relative air humidity of 75%.

Plant material

The plant material used was seed-tubers of potato variety CIP 39, with the following morphological characteristics: predominant yellow skin color, white flesh, oblong tuber shape, white flowers, early to semi-early vegetative period (120 to 130 d), and industrial uses (French fries) (Instituto Nacional de Innovación Agraria, 2012).

The fertilization plan was adjusted according to the results of soil analysis (Tab. 1) and following the recommendations for potato cultivation by Guerrero-Riascos (1995). The nutrient requirements in terms of nitrogen, phosphorus, and potassium were adjusted using simple fertilizer sources such as urea, diammonium phosphate, and KCl. In addition, micronutrients were applied using B-Zn (8% boron + 4% zinc).

For the control of pest insects and diseases, protective and systemic action products were used. The most limiting disease was late blight caused by the fungus *Phytophthora infestans*, which was managed using protective and systemic fungicides such as chlorothalonil, dimethomorph, mancozeb, cymoxanil, and metalaxyl. For the control of the most limiting pest insect, the Guatemalan moth (*Tecia solanivora*), applications of thiamethoxam, cyantraniliprole, and imidacloprid were carried out. Irrigation was adjusted based on the percentage of allowed depletion according

TABLE 1. Physical and chemical properties of soil at the experimental site.

Texture			pH	Organic matter %	P mg kg^{-1}	Ca	Mg	K	Na	Electric conductivity
Sand	Clay	Silt								
23	38	39				meq 100 g^{-1}				dS m^{-1}
Clay Loam			5.27	7.33	18.8	6.02	1.07	1.02	0.06	0.15

to the phenological state, following the methodology employed by Guerrero-Guio *et al.* (2019), and was supplied through a sprinkler system.

A completely randomized design (CRD) was employed, with four treatments corresponding to registered commercial biostimulants in Colombia, clearly labeled with the type of active compound. The treatments were as follows: T1: Hormonal (Hormonal), corresponding to the commercial product Stimulate® (Stoller Colombia S.A.), which contains a mixture of kinetin, indole-3-butyric acid, and gibberellic acid (GA_3); T2: Seaweed extract (SWE), corresponding to the product Radifarm™ (Valagro) composed of proteins, amino acids, betaines, alginates, and polysaccharides extracted from *Ascophyllum nodosum* algae; T3: Carboxylic acids (Carboxylic A), corresponding to the product Radigrow® (Innovak Global, S.A.) composed of Carboxy acids® expressed as total oxidizable organic carbon; and T4: No application (water). Each treatment had three replicates, totaling 12 experimental units which corresponded to plots of 72 m^2 with a planting distance of 0.3 m between plants and 1 m between rows, with 240 plants per plot.

The treatments were applied by soil spraying at two times with a solution volume of 1.5 L per plot. The first application was performed at phenological stage 08, which corresponds to stems growing towards the soil surface (Hack *et al.*, 1993). The second application was performed 15 d after the first application. The dosage for all treatments was 10 ml L^{-1} of commercial product, following the technical recommendation for ground spraying. Water was used as the diluent for preparing the solutions.

Growth parameters

Growth parameters were evaluated 94 d after planting, when the plants were at phenological stage 69, corresponding to full bloom (Hack *et al.*, 1993). At this stage, plants achieve their maximum fresh and dry mass gain as well as the largest leaf area.

To determine the leaf area index (LAI), leaf area was measured using an electronic leaf area meter (Area Meter CI-202, CID Bio-Science, Inc., USA). For this, two plants per experimental unit were selected, and all leaves from each plant were removed for measurement. Leaf area was expressed in square meters (m^2), and the number of plants per 1 m^2 was also determined. The obtained values were used to calculate the LAI using Equation 1 proposed by Reis *et al.* (2013):

$$\mathrm{LAI} = \frac{(\mathrm{LA} \times \mathrm{NP})}{\mathrm{TA}} \tag{1}$$

where LAI is in m^2 m^{-2}, LA is the average leaf area of two plants (m^2), NP is the number of plants per m^2, and TA is the total area considered (1 m^2).

Fresh weight gain was evaluated on four plants from the center of each experimental unit. These plants were placed in paper bags with a capacity of 10 kg, properly labeled according to treatment. The plants were then separated into root and above-ground parts (stems + leaves) and weighed using an Acculab VIC 612 electronic balance with a precision of 0.01 g. Subsequently, the samples were dried in a Memmert oven at 65°C until reaching a constant weight (approximately 96 h) to determine dry weight gain. The analyses were conducted at the Plant Physiology Laboratory of the Pedagogical and Technological University of Colombia.

Productivity parameters

For the productivity evaluation, all tubers were collected from each experimental unit and then placed in white fiber bags with a capacity of 50 kg. They were commercially classified into two categories according to the Colombian technical standard NTC 341 (ICONTEC, 1996). The category of first quality (Quality 1) corresponds to tubers with a diameter of 65 to 90 mm, and the category of second quality (Quality 2) corresponds to tubers with a diameter of 45 to 64 mm. The fresh weight data of tubers obtained from each experimental unit was extrapolated to obtain productivity expressed as yield in tons per ha (t ha^{-1}).

Statistical analysis

The obtained data were tested for normal distribution of residuals and homogeneity of variances using the Shapiro-Wilk test ($P \geq 0.05$) and Bartlett test ($P \geq 0.05$), respectively.

Once the assumptions were confirmed, hypotheses were evaluated for each of the variables assessed through an analysis of variance (ANOVA). Finally, a multiple mean comparison test was conducted using the Tukey test ($P \leq 0.05$). The analyses were performed using the 'agricolae' package of the statistical software R Core Team (2022).

Results and discussion

Growth variables

The variables of fresh and dry weight were significantly affected ($P \leq 0.05$) by the application of biostimulants (Fig. 1). In the Hormonal treatment, the fresh weight of the roots, the aerial part, and the total were 124.8±3.4 g, 675.7±17.6 g, and 800.5±18.7 g, respectively, with gains of 65%, 14%, and 16%, respectively, compared to the control treatment, which had values of 75.4±2.3 g, 595.2±12.6 g, and 690.1±8.3 g, respectively (Fig. 1A).

In the carboxylic acids treatment (Carboxylic A), the dry weight of the roots, the aerial part, and the total plant weight showed values of 35.8±0.9 g, 116.2±2.9 g, and 152.0±3.8 g, respectively, with gains of 2%, 41%, and 29%, respectively, compared to the control treatment, which had values of 35.3±1.6 g, 82.3±1.0 g, and 117.6±1.1 g, respectively (Fig. 1B).

Fresh weight is considered a good estimator of plant volume, as water is the main component of all organs and tissues, while dry weight is a good estimator of the total carbon content of the plant, allowing for the analysis of plant physiology (Di Benedetto & Tognetti, 2016). Increases in fresh weight may be related to changes occurring in the organization and cellular metabolism of plants grown under the influence of biologically active substances or products, as these substances regulate nutrient absorption and translocation and alter the phytohormone levels (Falcón Rodríguez *et al*., 2015).

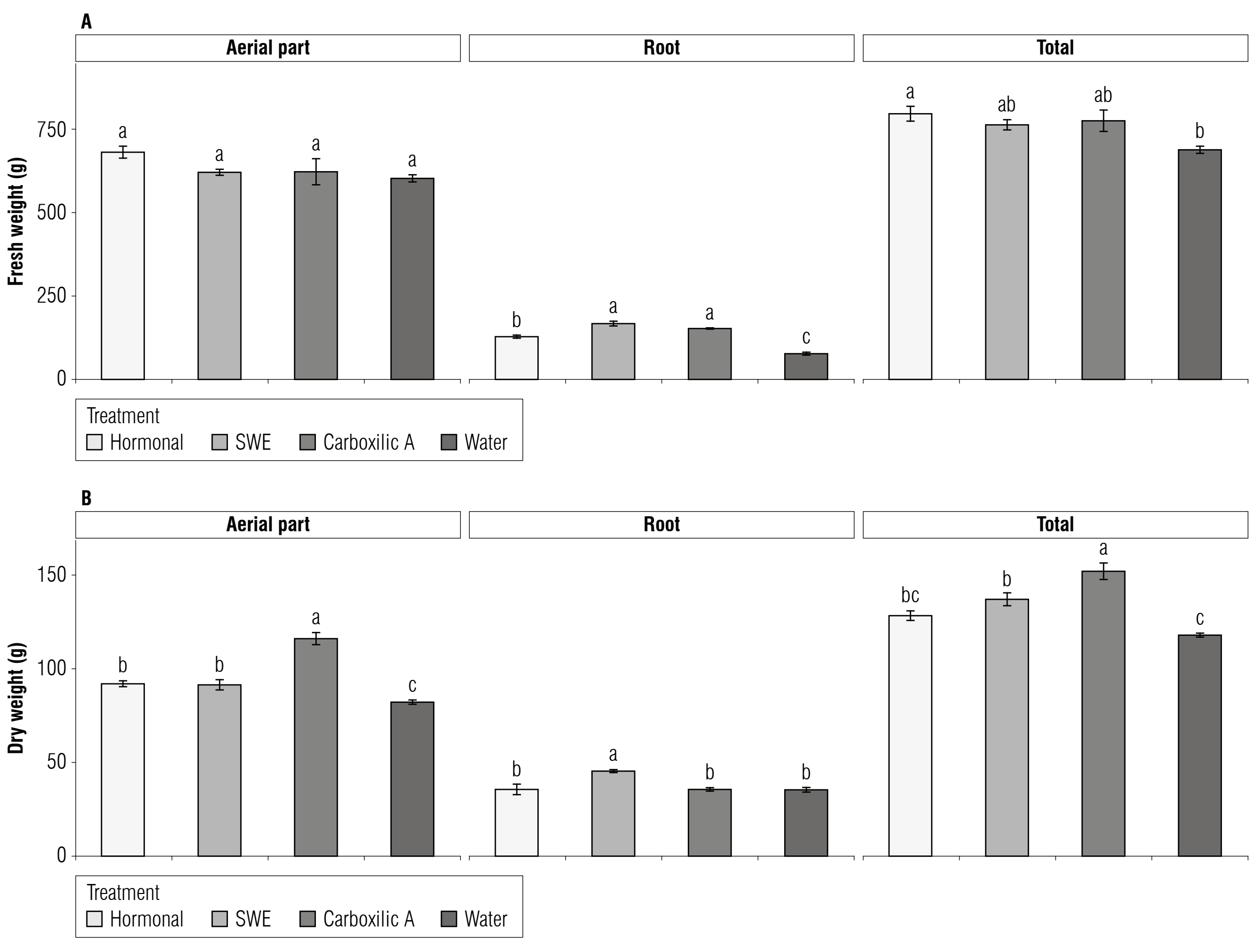

FIGURE 1. Fresh weight (A) and dry weight (B) of potato plants variety CIP 39 under the application of different types of biostimulants. Different letters indicate significant differences between treatments according to the Tukey mean test ($P \leq 0.05$). Vertical bars represent standard error (n=3). SWE – seaweed extract, Carboxylic A – carboxylic acids.

The results with the hormonal treatment are attributed to the ratio between kinetin, indole-3-butyric acid, and GA_3 in the applied product, which preferentially stimulates growth of roots, leaves, and stems. This could be related to its action on hormonal balance (Asari *et al*., 2017). One of the most widespread uses of commercial biostimulants is as growth promoters. These morphological responses are frequently attributed to the activity of endogenous auxins and cytokinins in treated plants (Sharma *et al*., 2014; Wally *et al*., 2013) or exogenous ones present in the extracts (Vinoth *et al*., 2019), which often contain fractions of polysaccharides that could induce root growth similarly to synthetic auxins (Hernández-Herrera *et al*., 2016).

Biostimulants are primarily derived from a variety of organic materials, including humic, fulvic, and carboxylic acids, among others (Drobek *et al*., 2019; Zuzunaga-Rosas *et al*., 2023). The treatment with the application of carboxylic acids favored both root and shoot growth (Fig. 1). The weight gain obtained with the application of organic biostimulants may be attributed to their promotion of the absorption of macro and micronutrients, boosting metabolic activity. This makes root absorption more efficient and regulates the nutrient absorption activity of the rhizosphere by stimulating activity of H^+ ATPases in the plasma membrane. These enzymes convert the free energy released by ATP hydrolysis into an electrochemical potential across the membrane, which is used for the uptake of nitrate and other nutrients by roots (Canellas *et al*., 2015; Drobek *et al*., 2019; du Jardin, 2015).

Leaf area index (LAI)

The application of a biostimulants resulted in significant differences ($P \leq 0.05$) compared to the control treatment (Fig. 2). The treatments with seaweed extract (SWE), carboxylic acids (Carboxylic A), and hormonal treatment resulted in mean values of 2.4±0.04 m^2 m^{-2}, 2.3±0.12 m^2 m^{-2}, and 2.2±0.06 m^2 m^{-2}, respectively. In contrast, the control treatment (water) presented the lowest LAI with a mean value of 1.6±0.02 m^2 m^{-2}.

The plant is essentially a capturer of solar energy, which is stored in the form of carbohydrates. This process takes place in leaves, from which carbohydrates are then mobilized towards the tubers (storage organs). The LAI is closely related to the plant's ability to intercept solar radiation, directly associated with the processes of photosynthesis and transpiration. These processes are directly linked to biomass accumulation and productivity (Hernández-Hernández *et al*., 2011). LAI is a fundamental parameter for evaluating crop growth and development, as it can be used to estimate water and nutrient requirements as well as bioenergetic efficiency (Reis *et al*., 2013). Therefore, LAI is a useful variable for quantifying crop growth and agronomic performance (Mendoza-Pérez *et al*., 2017).

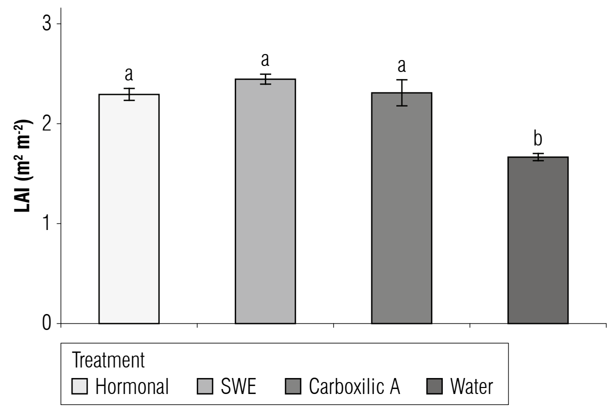

FIGURE 2. Leaf area index (LAI) of potato plants variety CIP 39 under the application of biostimulants. Different letters indicate significant differences according to the Tukey test ($P \leq 0.05$). Vertical bars represent standard error (n=3). SWE – seaweed extract, Carboxylic A – carboxylic acids.

Dry matter production is commonly related to the plant's capacity to increase its leaf area; therefore, a larger leaf area will result in greater dry matter accumulation. However, this is not always the case, as the optimal leaf area index is the one that maximizes the dry matter accumulation rate. This is achieved when the crop intercepts nearly all available photosynthetically active radiation (PAR) and, consequently, the lower leaf layers are still capable of maintaining a positive carbon balance (Bergamaschi *et al*., 2010; Hunt, 2016).

Polysaccharides extracted from macroalgae cell walls and their derived oligosaccharides can enhance growth (Zou *et al*., 2019). This is because seaweeds affect plant metabolism and physiology, as their extracts possess growth inducers and/or trigger differential expression of genes involved in the synthesis of endogenous phytohormones and other primary metabolism pathways (Ghaderiardakani *et al*., 2019).

According to Santos *et al*. (2010), who evaluated four potato cultivars, the highest LAI values were registered during flowering, with values of 2.8 m^2 m^{-2}. The application of SWA resulted in an LAI of 2.4±0.04 m^2 m^{-2}, which generated a better balance between the plant's ability to intercept light and photosynthesis processes, leading to increased crop productivity (Figs. 3 and 4).

Productivity variables

Yield by commercial grades showed statistical differences between the treatments ($P\leq0.05$). For Quality 1 tubers, with diameters of 65 to 90 mm, the SWE treatment exhibited a 17.6% increase with a mean value of 40.7±0.36 t ha^{-1}, compared to the control which had a value of 34.6±0.52 t ha^{-1} (Fig. 3). For Quality 2 tubers, with a diameter of 45 to 64 mm, the treatment based on carboxylic acids showed an 80% increase with a mean value of 7.4±0.6 t ha^{-1}, compared to the control, which had a value of 4.07±0.6 t ha^{-1} (Fig. 3).

Total yield analysis had a significant increase ($P\leq0.05$) compared to the control treatment. SWE treatment had an 18.2% rise in total yield, averaging 46.7±0.75 t ha^{-1}, compared to the control yield of 39.4±1.6 t ha^{-1} (Fig. 4).

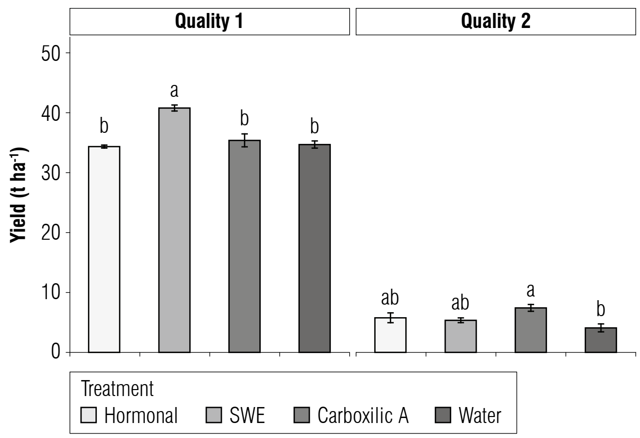

FIGURE 3. Yield by grades in potato plants variety CIP 39 subjected to different types of biostimulants. Identical letters among treatments indicate no significant differences according to the Tukey mean test ($P\leq0.05$). Vertical bars represent standard error (n=3). Quality 1: tubers with a diameter of 65 to 90 mm; Quality 2: tubers with a diameter of 45 to 64 mm (ICONTEC, 1996). SWE – seaweed extract, Carboxylic A – carboxylic acids.

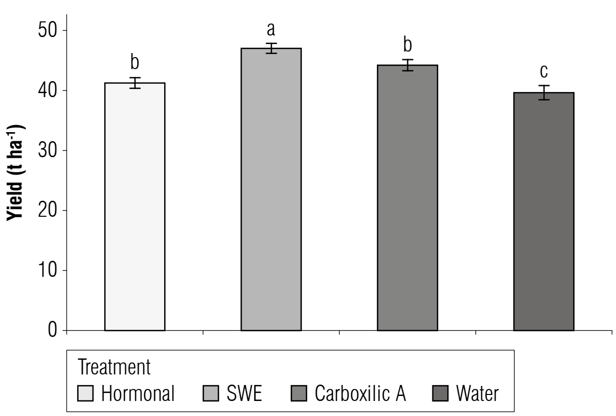

FIGURE 4. Total yield in potato plants (*Solanum tuberosum* L.) variety CIP 39 subjected to different types of biostimulants. Identical letters among treatments indicate no significant differences according to the Tukey mean test ($P\leq0.05$). Vertical bars represent standard error (n=3). SWE – seaweed extract, Carboxylic A – carboxylic acids.

The application of biostimulants at different stages of crop growth can improve yield per plant by triggering a series of physiological and biochemical events in plants that result in increased production (Martínez *et al.*, 2017).

Extract-based biostimulants promote many physiological processes in the plants, including photosynthesis. These biostimulants contain amino acids such as alanine and glycine, which enhance photosynthesis and also play a role in the synthesis of porphyrins, structural pillars of chlorophyll and cytochromes. This enhances plant activity, increasing reserve substances that are translocated to different parts of the plants, such as storage organs (Díaz *et al.*, 2020; Ertani *et al.*, 2018) .

Various studies confirm the positive effects of seaweed-based biostimulants on crop performance and post-harvest quality. According to Abbas *et al.* (2020), foliar applications significantly increased bulb and neck diameter as well as yield per hectare in four onion cultivars and improved the contents of total soluble solids, ascorbic acid, nitrogen, potassium, and phosphorus. Similarly, Yao *et al.* (2020) indicate that seaweed-based products significantly increased the net yield of *Solanum lycopersicum* L. by 6.9% compared to the control and positively affected fruit firmness and soluble sugar content.

However, the effects of biostimulants are not always consistent, as they depend on the plant species, the sensitivity thresholds to one or more bioactive molecules, as well as the different extraction procedures that ensure the purity and quality of the bioactive compounds in the products.

Conclusions

The application of biostimulants based on seaweed generated a positive effect on plant growth, improving the accumulation of both fresh and dry biomass, as well as the leaf area index (LAI). This led to an increase in both the quantity and quality of yield components. This suggests that this practice is an alternative worth considering within agronomic management plans for potato cultivation in different production zones of the country.

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endorse, nor do they disapprove the use of the biostimulant formulations and/or chemical products mentioned in this article. The authors have no affiliation with the biostimulant manufacturing companies or organizations whose products they review as treatments in the experiment.

Conflict of interest statement

The authors declare that there is no conflict of interests regarding the publication of this article.

Author's contributions

JDMA: research, writing - original draft, visualization, writing, and editing. EHPS: conceptualization, writing, formal analysis, data curation, and supervision. DFTH: writing, editing, and supervision. All authors have read and approved the final version of the manuscript.

Literature cited

Abbas, M., Anwar, J., Zafar-Ul-Hye, M., Khan, R. I., Saleem, M., Rahi, A. A., Danish, S., & Datta, R. (2020). Effect of seaweed extract on productivity and quality attributes of four onion cultivars. *Horticulturae*, *6*(2), Article 28. https://doi.org/10.3390/horticulturae6020028

Asari, S., Tarkowská, D., Rolčík, J., Novák, O., Palmero, D. V., Bejai, S., & Meijer, J. (2017). Analysis of plant growth-promoting properties of *Bacillus amyloliquefaciens* UCMB5113 using *Arabidopsis thaliana* as host plant. *Planta*, *245*(1), 15–30. https://doi.org/10.1007/s00425-016-2580-9

Bergamaschi, H., Dalmago, G. A., Bergonci, J. I., Krüger, C. A. M. B., Heckler, B. M. M., & Comiran, F. (2010). Intercepted solar radiation by maize crops subjected to different tillage systems and water availability levels. *Pesquisa Agropecuaria Brasileira*, *45*(12), 1331–1341. https://doi.org/10.1590/s0100-204x2010001200001

Brown, P., & Saa, S. (2015). Biostimulants in agriculture. *Frontiers in Plant Science*, *6*(6), 1571–1583. https://doi.org/10.3389/fpls.2015.00671

Bulgari, R., Franzoni, G., & Ferrante, A. (2019). Biostimulants application in horticultural crops under abiotic stress conditions. *Agronomy*, *9*(6), Article 306. https://doi.org/10.3390/agronomy9060306

Canellas, L. P., & Olivares, F. L. (2014). Physiological responses to humic substances as plant growth promoter. *Chemical and Biological Technologies in Agriculture*, *1*(1), Article 3. https://doi.org/10.1186/2196-5641-1-3

Canellas, L. P., Olivares, F. L., Aguiar, N. O., Jones, D. L., Nebbioso, A., Mazzei, P., & Piccolo, A. (2015). Humic and fulvic acids as biostimulants in horticulture. *Scientia Horticulturae*, *196*, 15–27. https://doi.org/10.1016/j.scienta.2015.09.013

Díaz, G., Rodríguez, G., Montana, L., Miranda, T., Basso, C., & Arcia, M. (2020). Efecto de la aplicación de bioestimulantes y Trichoderma sobre el crecimiento en plántulas de maracuyá (*Passiflora edulis* Sims) en vivero. *Bioagro*, *32*(3), 195–204. https://revistas.uclave.org/index.php/bioagro/article/view/2787/1745

Di Benedetto, A., & Tognetti, J. (2016). Técnicas de análisis de crecimiento de plantas: su aplicación a cultivos intensivos. *RIA. Revista de Investigaciones Agropecuarias*, *42*(3), 258–282. https://www.redalyc.org/articulo.oa?id=86449712008

Drobek, M., Frąc, M., & Cybulska, J. (2019). Plant biostimulants: Importance of the quality and yield of horticultural crops and the improvement of pla*nt tolerance to abiotic stress – A* review. *Agronomy*, *9*(6), Article 335. https://doi.org/10.3390/agronomy9060335

Du Jardin, P. (2015). Plant biostimulants: Definition, concept, main categories and regulation. *Scientia Horticulturae*, *196*, 3–14. https://doi.org/10.1016/j.scienta.2015.09.021

Ertani, A., Francioso, O., Tinti, A., Schiavon, M., Pizzeghello, D., & Nardi, S. (2018). Evaluation of seaweed extracts from Laminaria and *Ascophyllum nodosum* spp. as biostimulants in *Zea mays* L. using a combination of chemical, biochemical and morphological approaches. *Frontiers in Plant Science, 9*, Article 428. https://doi.org/10.3389/fpls.2018.00428

Falcón Rodríguez, A., Costales Menéndez, D., González-Peña Fundora, D., & Nápoles García, M. (2015). Nuevos productos naturales para la agricultura: las oligosacarinas. *Cultivos Tropicales*, *36*, 111–129. https://ediciones.inca.edu.cu/index.php/ediciones/article/view/1128/pdf

Ghaderiardakani, F., Collas, E., Damiano, D. K., Tagg, K., Graham, N. S., & Coates, J. C. (2019). Effects of green seaweed extract on *Arabidopsis* early development suggest roles for hormone signalling in plant responses to algal fertilisers. *Scientific Reports*, *9*(1), Article 1983. https://doi.org/10.1038/s41598-018-38093-2

Guerrero-Guio, J. C., Cabezas Gutiérrez, M., & Galvis Quintero, J. H. (2019). Efecto de dos sistemas de riego sobre la producción y uso eficiente del agua en el cultivo de papa variedad Diacol Capiro. *Revista de Investigación Agraria y Ambiental*, *11*(1), 41–52. https://doi.org/10.22490/21456453.3080

Guerrero-Riascos, R. (1998). *Fertilización de cultivos en clima frio* (2nd ed., pp. 370). Monómeros Colombo Venezolanos S.A.

Hack, H., Gall, H., Klemke, T. H., Klose, R., Meier, U., Stauss, R., & Witzenberger, A. (1993). Phänologische entwicklungsstadien der Kartoffel (*Solanum tuberosum* L.). *Nachrichtenblatt Des Deutschen Pflanzenschutzdienstes*, *45*(1), 11–19. https://www.openagrar.de/receive/openagrar_mods_00067178

Hailu, G., Nigussie, D., Ali, M., & Derbew, B. (2017). Nitrogen and phosphorus use efficiency in improved potato (*Solanum tuberosum* L.) cultivars in Southern Ethiopia. *American Journal of Potato Research*, *94*(6), 617–631. https://doi.org/10.1007/s12230-017-9600-6

Hernández-Hernández, F., López Cruz, I. L., Guevara-González, R. G., Rico-García, E., Ocampo-Velásquez, V. R., Herrera-Ruiz, G., Gonzalez-Chavira, M. M., & Torres-Pacheco, I. (2011). Simulación del crecimiento y desarrollo de pimiento (*Capsicum annuum* L.) bajo condiciones de invernadero. *Revista Mexicana de Ciencias Agrícolas*, *2*(3), 385–397.

Hernández-Herrera, R. M., Santacruz-Ruvalcaba, F., Zañudo-Hernández, J., & Hernández-Carmona, G. (2016). Activity of seaweed extracts and polysaccharide-enriched extracts from *Ulva lactuca* and *Padina gymnospora* as growth promoters of tomato and mung bean plants. *Journal of Applied Phycology*, *28*(4), 2549–2560. https://doi.org/10.1007/s10811-015-0781-4

Hunt, R. (2016). Growth analysis, individual plants. In B. Thomas, B. G. Murray, & D. J. Murphy (Eds.), *Encyclopedia of applied plant sciences* (2nd ed., Vol. 1, pp. 421–429). Academic Press. https://doi.org/10.1016/B978-0-12-394807-6.00226-4

ICONTEC. (1996). NTC 341. Instituto Colombiano de Normas Técnicas y Certificación ICONTEC.

Instituto Nacional de Innovación Agraria, & Red Latin Papa. (2012). *Catalogo de nuevas variedades de papa: sabores y colores para el gusto peruano.* Centro Internacional de la Papa, Lima, Peru. https://doi.org/10.4160/978-92-9060-419-8

Kisvarga, S., Farkas, D., Boronkay, G., Neményi, A., & Orlóci, L. (2022). Effects of biostimulants in horticulture, with emphasis on ornamental plant production. *Agronomy*, *12*(5), Article 1043. https://doi.org/10.3390/agronomy12051043

Lazzarini, R., Müller, M., Lazzarini, P., Tamanini, C., Matos, C., & Kawakami, J. (2022). Humic substances: Effects on potato growth and yield. *Horticultura Brasileira*, *40*(1), 33–38. https://doi.org/10.1590/s0102-0536-20220104

Lephatsi, M., Nephali, L., Meyer, V., Piater, L. A., Buthelezi, N., Dubery, I. A., Opperman, H., Brand, M., Huyser, J., & Tugizimana, F. (2022). Molecular mechanisms associated with microbial biostimulant-mediated growth enhancement, priming and drought stress tolerance in maize plants. *Scientific Reports*, *12*(1), Article 10450. https://doi.org/10.1038/s41598-022-14570-7

Li, J., Van Gerrewey, T., & Geelen, D. (2022). A meta-analysis of biostimulant yield effectiveness in field trials. *Frontiers in Plant Science, 13*, Article 836702. https://doi.org/10.3389/fpls.2022.836702

Martínez González, L., Maqueira-López, L., Nápoles-García, M. C., & Núñez Vásquez, M. (2017). Biostimulant effect on yield of two biofertilized bean (*Phaseolus vulgaris* L.) cultivars. *Cultivos Tropicales*, *38*(2), 113–118. https://www.cabidigitallibrary.org/doi/full/10.5555/20173291981

Mendoza-Pérez, C., Ramírez-Ayala, C., Ojeda-Bustamante, W., & Flores-Magdaleno, H. (2017). Estimation of leaf area index and yield of greenhouse-grown poblano pepper. *Ingeniería Agrícola y Biosistemas*, *9*(1), 37–50. https://doi.org/10.5154/r.inagbi.2017.04.009

R Core Team. (2022). *R: A language and environment for statistical computing.* R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org

Reis, L. S., Azevedo, C. A. V., Albuquerque, A. W., & Junior, J. F. S. (2013). Índice de área foliar e produtividade do tomate sob condições de ambiente protegido. *Revista Brasileira de Engenharia Agricola e Ambiental*, *17*(4), 386–391. https://doi.org/10.1590/S1415-43662013000400005

Santos, V. M., Melo, A. V., Cardoso, D. P., Gonçalves, A. H., Sousa, D. C. V., & Silva, Á. R. (2017). Uso de bioestimulantes no crescimento de plantas de soja. *Revista Verde de Agroecologia e Desenvolvimento Sustentável*, *12*(3), 512–517. https://doi.org/10.18378/rvads.v12i3.4139

Santos Castellanos, M., Segura Abril, M., & Ñustez López, C. E. (2010). Análisis de crecimiento y relación fuente-demanda de cuatro variedades de papa (*Solanum tuberosum* L.) en el municipio de Zipaquirá (Cundinamarca, Colombia). *Revista Facultad Nacional de Agronomía Medellin*, *63*(1), 5253–5266. http://scielo.org.co/scielo.php?script=sci_arttext&pid=S0304-28472010000100004

Sebnie, W., Esubalew, T., & Mengesha, M. (2021). Response of potato (*Solanum tuberosum* L.) to nitrogen and phosphorus fertilizers at Sekota and Lasta districts of Eastern Amhara, Ethiopia. *Environmental Systems Research*, *10*(1), Article 11. https://doi.org/10.1186/s40068-020-00213-1

Sharma, H. S. S., Fleming, C., Selby, C., Rao, J. R., & Martin, T. (2014). Plant biostimulants: a review on the processing of macroalgae and use of extracts for crop management to reduce abiotic and biotic stresses. *Journal of Applied Phycology*, *26*(1), 465–490. https://doi.org/10.1007/s10811-013-0101-9

Torres-Hernández, D. F., Pinzón-Sandoval, E. H., Balaguera-López, H. E., Silva-Parra, A., & Galvis-Quintero, J. H. (2023). Responses of growth and yield of ‘Diacol Capiro’ potatoes to application of silicate fertilizer amendments. *Revista Colombiana de Ciencias Hortícolas*, *17*(3), Article e16450. https://doi.org/10.17584/rcch.2023v17i3.16450

Van Dingenen, J., Hanzalova, K., Abd Allah Salem, M., Abel, C., Seibert, T., Giavalisco, P., & Wahl, V. (2019). Limited nitrogen availability has cultivar-dependent effects on potato tuber yield and tuber quality traits. *Food Chemistry*, *288*, 170–177. https://doi.org/10.1016/j.foodchem.2019.02.113

Van Oosten, M. J., Pepe, O., De Pascale, S., Silletti, S., & Maggio, A. (2017). The role of biostimulants and bioeffectors as alleviators of abiotic stress in crop plants. *Chemical and Biological Technologies in Agriculture*, *4*(1), Article 5. https://doi.org/10.1186/s40538-017-0089-5

Vélez Betancourt, A. F. (2020). *Cadenas sostenibles ante un clima cambiante: La papa en Colombia*. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. Puntoaparte Editores, Bogotá. https://www.giz.de/en/downloads/GIZ_CIAT_PapaPag_sencillas_web.pdf

Vinoth, S., Gurusaravanan, P., Sivakumar, S., & Jayabalan, N. (2019). Influence of seaweed extracts and plant growth regulators on *in vitro* regeneration of *Lycopersicon esculentum* from leaf explant. *Journal of Applied Phycology*, *31*(3), 2039–2052. https://doi.org/10.1007/s10811-018-1703-z

Wadas, W., & Dziugieł, T. (2020). Quality of new potatoes (*Solanum tuberosum* L.) in response to plant biostimulants application. *Agriculture (Switzerland)*, 10(7), 1–13. https://doi.10.3390/agriculture10070265

Wally, O. S. D., Critchley, A. T., Hiltz, D., Craigie, J. S., Han, X., Zaharia, L. I., Abrams, S. R., & Prithiviraj, B. (2013). Regulation of phytohormone biosynthesis and accumulation in *Arabidopsis* following treatment with commercial extract from the marine macroalga *Ascophyllum nodosum*. *Journal of Plant Growth Regulation*, *32*(2), 324–339. https://doi.org/10.1007/s00344-012-9301-9

Yao, Y., Wang, X., Chen, B., Zhang, M., & Ma, J. (2020). Seaweed extract improved yields, leaf photosynthesis, ripening time, and net returns of tomato (*Solanum lycopersicum* Mill.). *ACS Omega*, *5*(8), 4242–4249. https://doi.org/10.1021/acsomega.9b04155

Zou, P., Lu, X., Zhao, H., Yuan, Y., Meng, L., Zhang, C., & Li, Y. (2019). Polysaccharides derived from the brown algae *Lessonia nigrescens* enhance salt stress tolerance to wheat seedlings by enhancing the antioxidant system and modulating intracellular ion concentration. *Frontiers in Plant Science*, *10*, Article 48. https://doi.org/10.3389/fpls.2019.00048

Zuzunaga-Rosas, J., González-Orenga, S., Calone, R., Rodríguez-Heredia, R., Asaff-Torres, A., Boscaiu, M., Ibáñez-Asensio, S., Moreno-Ramón, H., & Vicente, O. (2023). Use of a biostimulant to mitigate the effects of excess salinity in soil and irrigation water in tomato plants. *Plants*, *12*(5), Article 1190. https://doi.org/10.3390/plants12051190