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Research Article

Biostimulant Formulations Modulate Root–Shoot Biomass And Increase Strawberry Yield In A Commercial Protected System.

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Abstract

Plant biostimulants have gained increasing attention as sustainable tools for enhancing crop performance, particularly in intensive horticultural systems. This study evaluated the effects of two commercial biostimulant formulations—a silicon dioxide-based solid product and a sugar beet molasses–based liquid product—on vegetative growth, biomass allocation, flowering, and yield of strawberry (*Fragaria* × *ananassa* Duch.) cv. Albion grown under protected cultivation in southern Brazil. The experiment was carried out under commercial production conditions, comparing a conventional management system (control) with two biostimulant treatments applied according to the manufacturer's recommendations. Vegetative growth, root and shoot dry mass, flowering intensity, fruit weight, and yield components were evaluated. Both biostimulants significantly increased plant vigor and aboveground biomass compared with the control, while the molasses-based formulation also markedly enhanced root dry mass. Earlier and more abundant flowering was observed in plants treated with sugar beet molasses, resulting in increased fruit weight and overall yield. Relative to the control, the molasses-based biostimulant increased average fruit weight by approximately 27% and total yield by about 26%, whereas the silicon-based treatment increased yield by approximately 17%. Overall, biostimulant application improved biomass partitioning and productive performance of strawberry plants under protected cultivation. These findings indicate that biostimulants, particularly molasses-based formulations, represent an effective and scalable strategy to enhance strawberry productivity in commercial protected systems.

Keywords : *Small fruits. Fragaria × ananassa; Plant biostimulus; Silicon dioxide; Sugar beet molasses.*

INTRODUCTION

Strawberry (*Fragaria* × *ananassa* Duch.) is one of the most economically important small fruit crops worldwide, driven by strong consumer demand and intensive production systems aimed at maximizing yield and fruit quality [1]. Its global relevance reflects high market demand, as strawberries are widely appreciated for their flavor and nutritional value, being rich in vitamins, dietary fiber, and antioxidant compounds [2]. Under protected cultivation systems, strawberry productivity can be substantially increased; however, intensive management practices may also increase plant susceptibility to abiotic stresses and raise sustainability-related concerns. In this context, enhancing plant performance while reducing dependence on high-input practices has become a central objective of modern strawberry production.

Abiotic stresses—particularly those related to water availability, substrate conditions, and nutrient dynamics—are major factors limiting strawberry growth and yield [3]. These stresses impair physiological and morphological processes essential for fruit development, including canopy expansion, root system function, and assimilate partitioning [4]. Consequently, strategies that improve plant vigor and resilience without increasing chemical inputs are increasingly sought in protected horticultural systems.

Plant biostimulants have emerged as promising tools to sustain crop performance under intensive and stress-prone conditions [5]. A growing body of research reports positive effects of biostimulants on vegetative growth, stress tolerance, and yield in horticultural crops, including strawberry [6]. However, plant responses vary considerably depending on product formulation, application method, and

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growing conditions. Furthermore, most available studies have been conducted under controlled environments or small-scale experimental trials, while evidence from commercial-scale protected systems remains limited. Comparative assessments of different biostimulant formulations and their effects on biomass allocation and yield components under practical production conditions are still scarce and warrant further scientific investigation [5].

Therefore, the objective of this study was to evaluate the productive responses of strawberry plants to the application of biostimulants based on sugar beet molasses and silicon dioxide. We hypothesized that both molasses- and silicon dioxide-based formulations would enhance vegetative growth (root–shoot biomass allocation) and flowering, thereby positively affecting the yield of strawberry cv. Albion cultivated under protected conditions in southern Brazil.

MATERIALS AND METHODS

The experiment was conducted from May to October 2025 in a protected strawberry cultivation system at Natuberry, located in the municipality of Santa Maria, Rio Grande do Sul, Brazil (29°39′02″ S, 53°54′30″ W). The potential biostimulant effects of two commercial product lines manufactured and marketed by the Swiss company Penergetic were evaluated: a liquid formulation based on sugar beet molasses and a solid formulation based on silicon dioxide. According to the manufacturer, Penergetic technology involves the energization of substrates (liquid or solid) through a process referred to as "bioprogramming." Each formulation (liquid or solid) includes one product intended for soil/substrate application and another for foliar application.

In this study, both application strategies (solid and liquid formulations) were assessed under the same experimental conditions. Three treatments were established: (A) control (no commercial biostimulant application); (B) silicon dioxide–based solid biostimulant; and (C) sugar beet molasses–based liquid biostimulant. The products were applied according to the manufacturer's recommendations. Silicon dioxide was applied twice: directly to the substrate during the vegetative stage at a rate equivalent to 1.5 kg ha^{-1} (SoilPlus®) and as a foliar spray at 200 g ha^{-1} (FieldStim®) at BBCH growth stages 3, 33, 60, and 70. The sugar beet molasses formulation was applied at the same growth stages, at a rate equivalent to 1.5 L ha^{-1} to the substrate and 200 mL ha^{-1} as a foliar spray. For both treatments, products were diluted in water to a final concentration of 1.5% to prepare the spray solution for substrate and foliar applications. Applications were performed using a pressure sprayer.

The study was carried out during the second commercial production cycle of strawberry plants (cv. Albion), managed according to standard commercial practices for protected cultivation. Irrigation was performed using the existing system at the production unit, ensuring uniform water supply among treatments. Nutrient management was identical across treatments, except for the application of the evaluated biostimulants.

Treatment effects on plant growth and productivity were assessed based on the following parameters: number of flowers per plant (recorded during early developmental stages), leaf development (vigor, leaf number, and apparent size of vegetative structures), root dry mass (RDM), shoot dry mass (SDM), average fruit weight (g), and fruit weight per plant. The average fruit weight per plant per production cycle was calculated based on the mean number of flowers per plant and the average fruit weight.

Shoot and root samples were dried in a forced-air oven until constant weight to determine dry biomass. Fruits were harvested at commercial maturity and individually weighed using an analytical precision balance. The experiment followed a randomized complete block design (RCBD) with three blocks established within the greenhouse. Each block consisted of two plant rows (25 m in length) with 0.25 m spacing between rows. Fifteen plants per treatment were randomly selected within each block for growth and yield evaluations, totaling 45 experimental units per treatment. Blocks were used to account for potential environmental variability within the greenhouse, and treatments were randomly assigned within each block. Data were subjected to analysis of variance (ANOVA), considering blocks as random effects and treatments as fixed effects. When significant, means were compared using Tukey's test at the 5% probability level with the SISVAR statistical software [7].

RESULTS

The results for flowering and leaf development revealed marked differences among treatments at the early stages of plant growth. Plants treated with sugar beet molasses exhibited earlier and more abundant flowering, with a significantly higher number of flowers per plant compared with both the control (no biostimulant) and the silicon dioxide treatment. These plants developed a greater number of well-formed floral structures, whereas control plants showed delayed and less intense flowering. The silicon dioxide treatment resulted in intermediate flowering intensity. This positive response to sugar beet molasses was also reflected in leaf development. Treated plants exhibited more vigorous canopy growth, characterized by a higher number of leaves and visibly larger vegetative structures (**Table 1, Figure 1**).

Table 1. Parameters of vegetative growth of strawberry cv. Albion under different treatments.

Parameters	Treatments			CV (%)
	Control	Silicon dioxide	Sugar beet molasses	
Number of flowers per plant	14.3 c*	22.9 b	27.1 a	4.12
Plant height (cm)	15.22 b	16.45 a	16.78 a	2.01
Leaf blade diameter (cm)	4.95 b	5.36 b	6.59 a	3.35
Root dry mass (g)	37.93 b	40.08 b	65.32 a	5.66
Shoot dry mass (g)	36.23 c	63.03 b	81.31 a	5.28

**Means followed by the same letter in the lines do not differ from each other by Tukey's test at 5% probability. CV= coefficient of variation.*

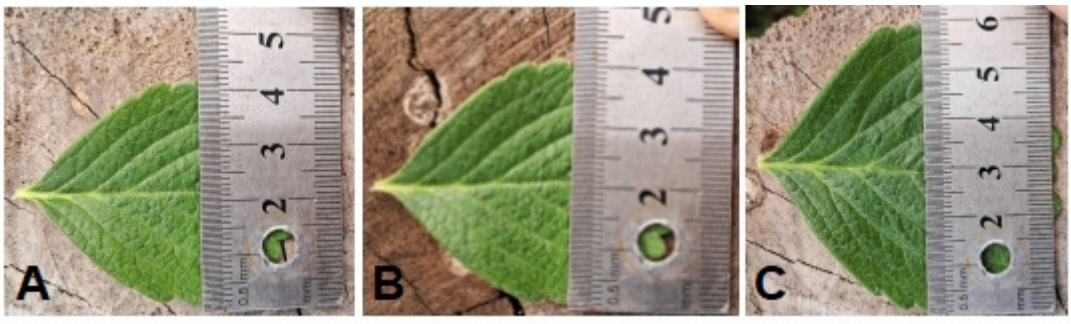
Regarding the average number of flowers per plant, the sugar beet molasses treatment showed the highest values, reaching approximately 27.1 flowers per plant, which was significantly higher than those observed in the other treatments. The control treatment averaged about 14.3 flowers per plant, while the silicon dioxide treatment averaged approximately 22.9 flowers per plant. These two treatments did not differ statistically from each other and both presented lower values than the molasses treatment, indicating that the application of sugar beet molasses significantly increased the number of flowers per plant—a response directly associated with higher strawberry productivity (**Table 1**).

The use of biostimulants, both in solid form (silicon dioxide) and liquid form (sugar beet molasses), resulted in taller strawberry plants compared with the control. Plants treated with the biostimulants reached average heights of approximately 16.8 cm and 16.5 cm, respectively, whereas plants in the control treatment averaged 15.2 cm (**Table 1**).

For leaf blade diameter, the positive effect of the sugar beet molasses treatment was more pronounced. Plants treated with molasses developed larger leaves, with an average diameter of about 6.6 cm, significantly exceeding the values observed for silicon dioxide (approximately 5.4 cm) and the control (4.95 cm) (**Table 1**). No statistical difference was detected between the silicon dioxide and control treatments for this variable, indicating that only the molasses-based treatment significantly increased leaf size.

The stimulatory effect of biostimulant application on leaf development is particularly relevant for crop production, as larger plants with more developed foliage have greater photosynthetic capacity to convert light energy into assimilates for fruit development. Control plants exhibited smaller and less developed leaves compared with those treated with biostimulants (**Figure 1**). Overall, these results indicate that the tested products enhanced the early vigor of strawberry plants, especially the sugar beet molasses formulation, which promoted a more pronounced increase in both flowering and leaf growth.

Figure 1. Leaf development of strawberry cv. Albion under the different treatments: (A) Control, (B) Silicon dioxide, and (C) Sugar beet molasses.



Biomass analysis confirmed the effect of the treatments on dry matter accumulation in strawberry plants. For root dry mass (RDM), the sugar beet molasses treatment showed the highest values, with an average of approximately 65.3 g of dry roots per plant, significantly greater than those observed in the control (37.9 g) and silicon dioxide treatments (40.1 g) (**Table 1**).

No significant difference was detected between the silicon dioxide and control treatments for root biomass, indicating that only the molasses-based treatment significantly enhanced root development (**Table 1, Figure 2**). The increase in root biomass observed with sugar beet molasses suggests the development of a more robust root system, possibly associated with improved nutrient availability and enhanced soil biological activity promoted by this treatment.

Figure 2. Strawberry cv. Albion plants at the time of yield evaluation under the different treatments: (A) Control, (B) Silicon dioxide, and (C) Sugar beet molasses.



Regarding shoot dry mass (SDM), which includes leaves and stems, both biostimulant treatments significantly increased biomass compared with the control. Plants treated with sugar beet molasses reached approximately 81.3 g of SDM, followed by those treated with silicon dioxide with about 63.0 g, whereas plants in the control treatment showed only 36.2 g of SDM (**Table 1**). This pattern (sugar beet molasses > silicon dioxide > control) indicates that both treatments significantly enhanced vegetative growth relative to the conventional management used in the production system, with the molasses-based treatment producing the most pronounced effect. In percentage terms, the sugar beet molasses treatment more than doubled shoot biomass compared with the control, while silicon dioxide increased shoot biomass by approximately 74% (**Table 1**). These results suggest that the use of biostimulant technologies strengthens the structural development of strawberry plants, both belowground through enhanced root growth and aboveground through more vigorous shoot development (**Figure 2**), a condition generally associated with healthier and more productive plants.

The positive effects of the treatments were directly reflected in the productive efficiency of the plants. The average weight of the strawberry fruits was higher in plants that received sugar beet molasses, reaching approximately 14.0 g per fruit, followed by the silicon dioxide treatment, with about 12.9 g per fruit (**Table 2**).

Table 2. Productivity parameters of strawberry cv. Albion under different treatments.

Parameters	Treatments			CV (%)
	Control	Silicon dioxide	Sugar beet molasses	
Average fruit weight (g)	11.04 b*	12.94 a	13.99 a	2.98
Fruit weight per plant per cycle (g)	157.87 c	296.32 b	379. 12 a	3.07
Productivity per hectare (tons)	44.16 b	51.73 a	55.96 a	4.43

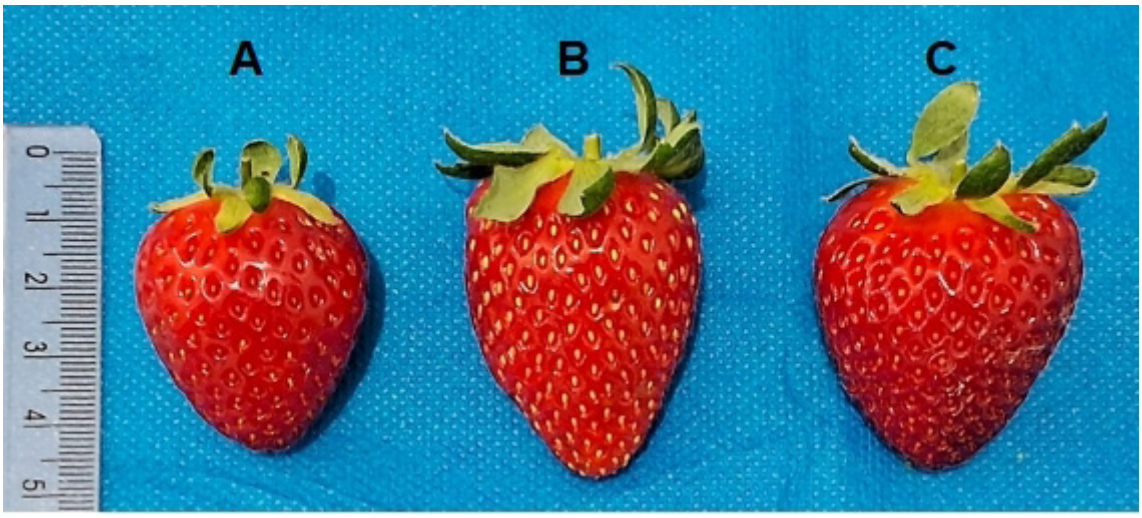
Plants in the control treatment produced significantly smaller fruits, with an average weight of approximately 11.0 g (**Table 2**, **Figure 3).** In practical terms, fruits from plants treated with sugar beet molasses were about 27% heavier than those from the control, while fruits from the silicon dioxide treatment were, on average, 17% heavier than those from the control (**Table 2**).

In terms of productivity, both biostimulants significantly increased yield per unit area compared with the producer's standard management. No significant difference was observed between the silicon dioxide and sugar beet molasses treatments for productivity per hectare. The sugar beet molasses treatment exceeded the control by approximately 12 t ha^{-1} (an increase of ~26%), whereas the silicon dioxide treatment exceeded the control by about 7.6 t ha^{-1} (~17% increase) (**Table 2**). These gains in productivity may be partly attributed to the greater fruit weight observed under both biostimulant treatments, as well as to an increase in the number of fruits per plant resulting from more abundant flowering.

Strawberry plants typically exhibit one to five production cycles within a single annual growing period, depending on cultivar genetics and environmental and nutritional conditions. Based on the average number of flowers per plant (**Table 1**) and the average fruit weight (**Table 2**), the mean fruit weight per plant per production cycle was calculated (**Table 2**).

The average fruit weight per plant per production cycle was significantly affected by the treatments. The control treatment showed the lowest mean value (157.87 g per plant), differing statistically from the other treatments. The silicon dioxide treatment significantly increased the average fruit weight per plant to 296.32 g, a value higher than the control but lower than that observed for the sugar beet molasses treatment. The highest value was recorded in the sugar beet molasses treatment, with an average of 379.12 g per plant, which differed significantly from the other treatments (**Table 2**).

Figure 3. Strawberry cv. Albion fruits at the time of yield evaluation under the different treatments: (A) Control, (B) Silicon dioxide, and (C) Sugar beet molasses.



In summary, the application of the evaluated commercial biostimulants (silicon dioxide and sugar beet molasses) resulted in significant improvements in strawberry yield, with the molasses-based treatment showing the most pronounced overall effects on vegetative growth, fruit size, and total production (**Table 2**).

Larger fruits are generally indicative of more favorable growing conditions and may reflect a greater supply of photoassimilates and nutrients to the reproductive organs of treated plants. Accordingly, estimated yield per hectare increased substantially with the use of the biostimulants. Yield projections indicate that the sugar beet molasses treatment reached approximately 55.96 t ha^{-1}, followed by the silicon dioxide treatment with about 51.73 t ha^{-1}, whereas the control treatment showed the lowest productivity, at approximately 44.16 t ha^{-1} (**Table 2**).

From an agronomic perspective, the use of these biostimulants represents a potentially sustainable strategy for producers aiming to improve strawberry yield and fruit quality. Such inputs can be integrated into crop management programs to enhance plant performance and increase production efficiency while maintaining a relatively low environmental impact.

DISCUSSION

The results of this study demonstrate that the application of commercial biostimulants can significantly improve the agronomic performance of strawberry plants under protected cultivation. Treated plants exhibited greater vegetative vigor—characterized by a higher number of larger leaves, increased plant height, and greater shoot and root dry biomass—as well as enhanced reproductive capacity, with earlier and more abundant flowering. These responses were reflected in higher productivity compared with conventional management. Such findings are consistent with the current literature documenting the positive effects of various biostimulants on plant growth, stress mitigation, and yield improvement in horticultural crops [8–10]. Pereira et al. [11], for example, reported that seaweed extracts increased strawberry fruit weight by up to 85% under water deficit conditions, in addition to improving plant water retention, reducing cellular damage, and increasing root biomass. Likewise, bio-inputs based on humus, protein hydrolysates, or beneficial microorganisms have been associated with improvements in yield and fruit quality in strawberry cultivation by enhancing plant nutrition and tolerance to abiotic stresses [12]. Collectively, these findings support the role of biostimulants as effective tools for increasing strawberry productivity while aligning with sustainable agricultural strategies aimed at reducing chemical

inputs without compromising yield or fruit quality.

In the present study, the treatment based on sugar beet molasses showed the most pronounced effects compared with the silicon dioxide treatment and the control, promoting the greatest increases in vegetative growth and yield. Plants treated with molasses developed larger and more numerous leaves, resulting in more vigorous canopies with greater photosynthetic capacity to support fruit production. The relevance of this effect is supported by Ciriello et al. [13], who reported that improvements in photosynthetic performance—such as a ~34% increase in CO_2 assimilation—induced by biostimulants are directly linked to a greater supply of photoassimilates and may be reflected in higher yields depending on the formulation used. In the present study, the molasses-based treatment also resulted in a higher number of flowers per plant and a more developed root system, factors that likely enhanced water and nutrient uptake and supported greater fruit production. This positive response may be related to the multifunctional characteristics of sugar beet molasses. As a carbon-rich byproduct containing organic carbon, vitamins, and minerals, molasses can act as a soil conditioner and energy source for beneficial microorganisms, thereby increasing nutrient availability to plants [14]. In addition, molasses contains osmoprotective compounds and essential ions that may contribute to improved plant vigor; for example, glycine betaine helps maintain cellular hydration under stress, and its high potassium content supports ionic balance and tolerance to adverse conditions [15].

The silicon dioxide–based biostimulant also improved vegetative and productive parameters relative to the control, including plant height, shoot dry mass, and average fruit weight, although to a lesser extent than the molasses-based treatment. Silicon, while not considered an essential nutrient, is recognized as a beneficial element for many plant species, contributing to the mitigation of abiotic stress and improvements in plant growth and productivity [16]. Ambros et al. [17] reported that a silicon-chelate–based biostimulant significantly increased root and shoot biomass, the number of reproductive structures, and antioxidant enzyme activity in strawberry seedlings, indicating enhanced plant vigor and improved capacity to withstand stress conditions.

From a sustainability perspective, the results of this study are particularly relevant. Increasing productivity by approximately 25% (as observed for the molasses-based treatment) through the use of biological inputs represents an opportunity to enhance fruit production per unit area without increasing reliance on mineral fertilizers or chemical pesticides. The FAO has emphasized the urgency of adopting intensification strategies that conserve natural resources and reduce the environmental impacts associated with conventional agricultural practices [18].

Biostimulant-based technologies such as those evaluated here may contribute to addressing these challenges. Both sugar beet molasses and silicon dioxide formulations showed potential for integration into sustainable strawberry production systems. The observed increases in plant biomass and fruit yield were achieved without altering other management practices (e.g., irrigation or basal fertilization), suggesting that these inputs can be incorporated into commercial systems with relative ease. Furthermore, the use of molasses may provide additional long-term benefits by stimulating soil microbial activity, potentially improving substrate structure and fertility and enhancing suppressiveness against soilborne pathogens, as reported for similar organic bioproducts [19,20].

Recent studies have also reported positive effects of Penergetic-based biostimulant products across various crops—including vegetables and major field crops such as tomato, soybean, and maize—beyond strawberry production. Reported benefits include improvements in plant vigor, yield, and certain quality attributes of harvested products, such as increased sugar or protein content [21]. Studies across different species suggest that such biostimulants can enhance plant growth and productivity and improve tolerance to abiotic stress conditions through overall improvements in plant physiological status [19].

The proposed mode of action of Penergetic technology, which is largely conceptual, is described as being based on physical principles related to electrical impulses and electromagnetic frequencies. According to this framework, atoms, molecules, and substances are assumed to possess specific electromagnetic frequencies that can be transferred from a source material to a carrier material through a process referred to as bioprogramming. Following this process, the treated products are described as emitting these frequencies into the application environment, potentially influencing the electronic state of materials and stimulating biological processes in soil and plants. In soil, such stimulation has been associated with increased microbial activity, enhanced mineralization of organic matter, and improved availability of previously immobilized nutrients, while in plants it has been linked to enhanced photosynthetic activity and metabolic processes [19, 22–24]. These proposed mechanisms have been suggested to help explain the biostimulatory effects on growth and productivity observed in strawberry cultivation.

Overall, the results of this study, together with evidence from the current literature, indicate that the use of commercial biostimulants in protected strawberry production may represent a promising strategy to combine high productivity with sustainability. By enhancing plant vigor and productive capacity—particularly in the case of the sugar beet molasses–based formulation—these inputs may contribute to reduced reliance on high-impact conventional practices. Further research is warranted to clarify the underlying mechanisms of

action and to refine recommendations regarding application rates, timing, and combinations in order to optimize the benefits of these biostimulants under different cultivation systems and strawberry cultivars.

CONCLUSION

The evaluated biostimulant formulations based on silicon dioxide and sugar beet molasses promoted plant development and increased strawberry productivity under protected cultivation. Both treatments enhanced flowering and vegetative growth compared with the control, resulting in greater leaf and root dry mass. Consequently, treated plants produced fruits with higher average weight and significantly greater total yield per hectare than those under conventional management. Overall, the results indicate that the use of these biostimulant formulations can improve the vigor and productive performance of strawberry plants grown under protected conditions and may represent a promising strategy to enhance productivity in commercial systems

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