

Coffee crop management using algae-based biostimulants

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Abstract

The use of biostimulants in coffee cultivation stands out as a sustainable option for agricultural efficiency, not only in terms of productivity but also in phytosanitary management. This work was developed in order to evaluate the effect of a freshwater algae extract, based on *Chlorella* sp. and enriched with *Azospirillum* sp., on the growth, yield, and beverage quality of Arabica coffee. The experiment was conducted at the IFSULDEMINAS Campus Inconfidentes in a randomized block design with eight treatments and three replications, at different phenological stages. Growth, yield, phytosanitary, and coffee quality variables were evaluated. Data were subjected to analysis of variance (ANOVA), principal component analysis, and a similarity network, in which correlations among data within a set were analyzed, enabling a more illustrative visualization of the relationships among variables. No significant differences were observed among the analyzed parameters, a result that may be explained by the doses used, which opens possibilities for future research. It is concluded that the application of the freshwater algae-based biostimulant at various phenological stages did not influence the growth or yield of Arabica coffee.

Keywords: *Coffea arabica* L. Coffee quality. Sustainability.

Introduction

In Brazil, Arabica coffee (*Coffea arabica* L.) production in 2024, according to the Brazilian National Supply Company (CONAB), totaled 39.6 million 60-kg bags, representing an increase of 1.8 % compared with the previous year's harvest (CONAB, 2025). This crop constitutes one of the main commodities in Brazilian export portfolios.

To maintain this importance, advances in Brazilian coffee production must be guided by its relationship with socioeconomic efficiency and the positive environmental impacts generated, meeting new market demands (Siqueira, Souza, Ponciano, 2011). In this context, the use of alternatives for more sustainable cultivation, such as biostimulants, is of paramount importance for resilient coffee production.

According to Kapoore, Wood, and Llewellyn (2021), rising costs of chemical fertilizers, pesticide resistance, and the impacts of climate

change, combined with the promising potential of microalgae-based biostimulants, indicate that these biotechnologies offer significant potential to make agriculture more sustainable.

Microalgae-based biostimulants are widely studied for their various benefits to agricultural crops, promoting plant growth, increasing metabolic activity, enhancing germination, improving photosynthesis, assisting nutrient uptake from the soil, and contributing to phytosanitary management. In addition, they influence productivity in a way that minimizes the negative effects of abiotic stress factors such as heat, drought, cold, frost, oxidative, mechanical, and chemical stresses (Yakhin *et al.*, 2017).

Biostimulants are characterized as mixtures of two or more plant growth regulators that may be associated with other substances, such as amino acids, nutrients, and vitamins (Silva

et al., 2008). These beneficial effects on coffee cultivation remain insufficiently explored by scientific research, although they are widely used by producers. With the expansion of coffee-growing areas and the adoption of new cultivation methods, the use of approaches to reduce biotic and abiotic stresses becomes important (Massia, Haddad, Mizubuti, 2009).

In a study conducted by Bettini (2015), involving the application of seaweed to coffee seedlings grown in pots inside a greenhouse, and subjected to water deficit and salt stress, the authors concluded that the use of algae for the cultivars Obatã and Catuaí 99 resulted in increases in leaf number as well as in the fresh and dry mass of leaves and branches, based on biometric evaluations. Plants subjected to salt stress had significant increases in leaf area and root fresh mass when treated with algae extract.

In another study examining the effects of algae-based fertilizers on the initial growth of coffee plants, Pedro *et al.* (2022) concluded that a commercial product based on extracts of the species *Ascophyllum nodosum*, applied as a foliar spray to one-year-old Arabica coffee seedlings of the Arara variety, resulted in substantial increases in leaf area index, shoot length, stem diameter, total fresh and dry mass, and an improved root-to-shoot ratio. The recommended dose was 1000 mL ha⁻¹.

Thus, the use of biostimulants stands out as a sustainable option for agricultural efficiency, not only in terms of productivity but also in relation to environmental preservation. Despite these benefits, this practice remains limited in dissemination, requiring studies that validate its application across various crops (Arejano *et al.*, 2022). In this context, this work was developed in order to evaluate the effect of *Chlorella* sp. extract enriched with *Azospirillum* sp. on the growth, yield, and beverage quality of coffee plants.

Material and methods

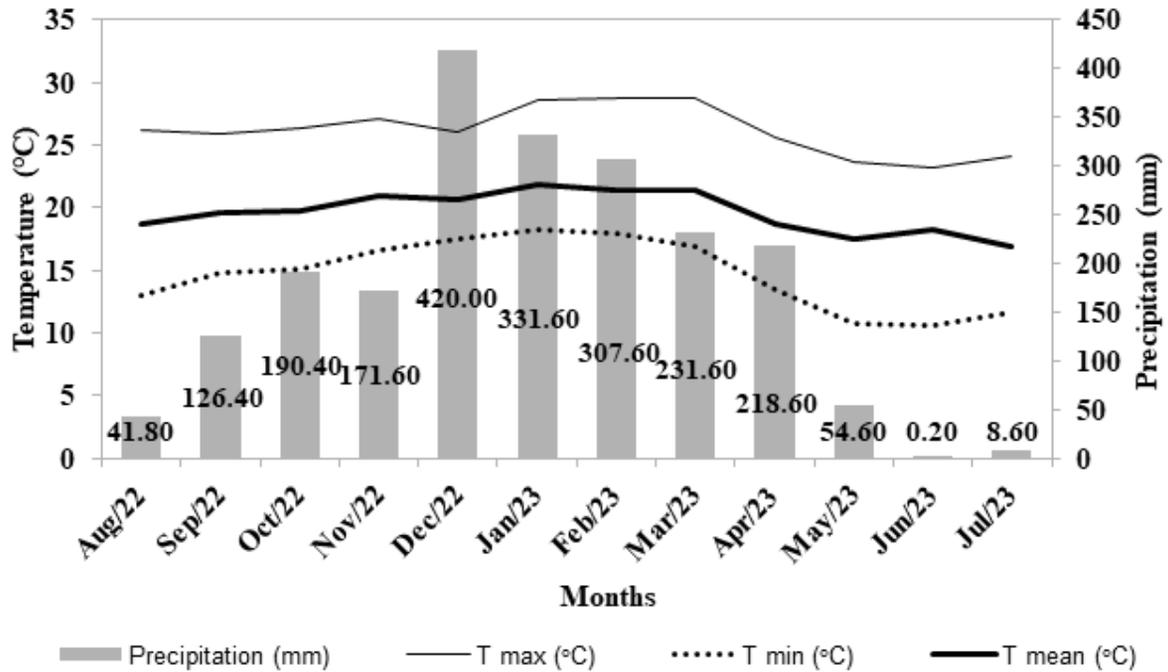
The experiment was conducted at the Educational Production Unit (UEP) Coffee Growing, at the School Farm of the Federal Institute of Education, Science, and Technology of Minas Gerais (IFSULDEMINAS), Campus Inconfidentes, from August 18, 2022, to July 4, 2023. The geographic coordinates are latitude 22°19'01" S and longitude 46°19'40" W, at an altitude of 869 m. The regional climate is Humid Tropical (Cwb), according to the classification of Wladimir Köppen (Brasil, 1992).

Information on temperature, precipitation, and relative humidity was obtained from a meteorological station (Vantage Pro2 – Davis®) installed at the IFSULDEMINAS School Farm, Campus Inconfidentes, located at latitude 22°18'37.47" S, longitude 46°19'56.31" W, and altitude 914.0 m. Hourly data were recorded by the equipment and aggregated to estimate mean, maximum, and minimum temperatures and precipitation (Figure 1).

The coffee cultivar used was Icatu Amarelo, planted at the experimental site in the 1990s with a spacing of 2 m × 1 m. The soil of the experimental area was classified as dystroferric Oxisol (Santos *et al.*, 2018).

In the 2021/2022 growing season, 260 g of lime per plant (35 % calcium oxide and 12 % magnesium oxide), 70 g of urea per plant, and spraying with fungicides containing the active ingredients flutriafol and copper oxychloride at commercial product rates of 0.5 L ha⁻¹ and 2 L ha⁻¹, respectively, were applied, in addition to zinc sulfate and boric acid fertilizers at 0.5 % applied to the leaves. In the 2022/2023 growing season, 100 g of lime per plant, 50 g of urea per plant, and 180 g per plant of the formulated fertilizer 30-00-20 were applied. The *saфра zero* (zero-yield) pruning system has been adopted in the plantation since 2018.

Figure 1. Meteorological data for Inconfidentes, Minas Gerais: maximum, minimum, and mean temperatures and precipitation from August 2022 to July 2023. IFSULDEMINAS – Campus Inconfidentes. Inconfidentes – MG, 2025.



Source: authors (2025).

The results of the soil chemical analyses for the area, at depths of 0–20 cm and 20–40 cm, are presented in Table 1. In the 0–20 cm layer, the soil contains 27.70 % sand, 38.97 % silt, and 33.33 % clay, with an organic matter content of 2.93 %.

The experiment was conducted in a randomized block design with three replications. Each plot consisted of six plants, with the four central plants evaluated and the two plants at the ends used as borders, in addition to one border row between treatment rows.

Table 1. Results of soil analysis for the experimental plot at depths of 0–20 cm and 20–40 cm. IFSULDEMINAS – Campus Inconfidentes. Inconfidentes – MG, 2025.

Depth	pH	P ¹	K ¹	Al	Ca ²	Mg/2	H+Al ²	SB	CTC	V
	H ₂ O	---- mg dm ⁻³ ----	-----	-----	-----	cmol _c dm ⁻³ -----	-----	-----	-----	%
0 to 20 cm	5.40	16.1	107.4	0.20	3.3	0.78	5.08	4.30	9.38	45.86
20 to 40 cm	4.95	5.8	82.2	1.30	1.9	0.29	8.37	2.36	10.73	21.99
-----	m	Ca/Mg	Mg/K	Zn ¹	Fe ¹	Mn ¹	Cu ¹	B	S	P-rem
Depth	%	---- cmol _c dm ⁻³ ----	-----	-----	-----	mg dm ⁻³ -----	-----	-----	-----	mg L ⁻¹
0 to 20 cm	4.44	4.18	2.83	5.0	34.7	12.8	0.2	0.2	-----	26.59
20 to 40 cm	35.5	6.31	1.40	-----	-----	-----	-----	-----	-----	-----

¹P, K, Fe, Zn, Mn, and Cu extracted with Mehlich 1 (1:10).

²Ca, Mg, and Al extracted with 1 N KCl (1:10).

Source: Soil Laboratory of IFSULDEMINAS — Campus Inconfidentes.

In the treatments, the commercial product Ferticell Universal® (Agroplama 3-0-1) was applied. The formulation contains 25 % freshwater unicellular algae extract (*Azospirillum* sp.), is completely neutral and biologically active, and also includes 2.72 % nitrogen (N), 2.57 % phosphorus (P), 1.14 % potassium (K), 0.52 % sulfur (S), 0.15 % zinc (Zn), 0.05 % boron (B), 58.7 mg L⁻¹ magnesium (Mg), 0.25 mg L⁻¹ copper (Cu), and 150.03 mg L⁻¹ manganese (Mn) (Nogueira *et al.*, 2025). The commercial product was applied during the reproductive phenological stages of the crop, including first flowering, expansion, grain filling, and maturation (Table 2).

Applications were organized into two distinct periods according to plant phenological stage (Table 2). For the expansion stage, the first application (Expansion 1) occurred 30 days before the second application (Expansion 2), establishing a time interval between treatments.

The concentration of 1.2 mL per four plants was applied in all treatments, diluted in water, corresponding to 1.5 L, with a spray volume of 912.5 L ha⁻¹, using a manual backpack sprayer. Application was performed after calibration of the manual sprayer through a blank test.

At the beginning of the experiment, four plagiotropic branches located in the middle

third of the plant at the four cardinal points were marked, and the last growth node from the previous season was identified. In July 2023, the number of nodes that developed during the experiment was counted for each plot.

The variables evaluated in plants included percentage of defoliation, chlorophyll index, and shoot dieback. For defoliation percentage, the number of nodes from the marked node on the four branches was counted, and the number of senesced leaves was recorded. An equation was used to estimate the percentage of defoliation for each plant (Equation 1). Any value below two leaves per node, such as 1 or 0, was considered indicative of defoliation.

$$\text{Defoliation: } \left(\frac{\text{Number of senesced leaves}}{\text{number of nodes} \times 2} \right) \times 100 \quad (\text{Eq. 1})$$

The incidence of coffee leaf rust (*Hemileia vastatrix*), Cercospora leaf spot (also known as brown eye spot; *Cercospora coffeicola*), and coffee leaf miner (*Leucoptera coffeella*) was evaluated monthly in each plot, considering four leaves per plant in the middle third, located at the third or fourth pair of leaves. Chlorophyll content was measured using a SPAD meter. All plots were assessed by measuring the central region of leaves in the middle third of the plant, at the third node of the plagiotropic branches marked at the beginning of the experiment.

Table 2. Description of treatments for algae application at various phenological stages of coffee plants. IFSULDEMINAS – Campus Inconfidentes. Inconfidentes – MG, 2025.

Treatment	Phenological stage	Phenological stage
1	Control	Control
2	Expansion 1	Post-first flowering
3	Expansion 1	Grain filling
4	Expansion 1	Maturation
5	Expansion 1	Expansion 2
6	Grain filling	Post-first flowering
7	Grain filling	Expansion 1
8	Grain filling	Maturation

Source: authors (2024).

Dieback was assessed through visual inspection of the previously marked plagiotropic branches when brittle, dry, and darkened tips were observed. Harvesting was carried out in July 2023 by selective hand-harvesting onto a raffia harvesting cloth. Yield was measured in each plot in 60-kg bags per hectare (Mesquita *et al.*, 2016) (Equation 2).

Yield estimate: (480 L of coffee / 8) =
bags ha⁻¹ (Eq. 2)

After harvest, the coffee fruits were directed to post-harvest procedures and subsequently sun-dried on a concrete patio.

For patio drying, the area was cleaned and prepared, and 24 one-square-meter sections were established, one per plot. The coffee was turned 8 to 10 times daily using a rake, and temperature was measured with a Minipa MTH-1300 precision thermo-hygrometer. The mean temperature and relative humidity during the drying period were 16.94°C and 81.18 %, respectively.

After reaching the half-dry stage, the coffee beans were covered at the end of the day with burlap sacks and tarps and remained covered until 9:00 a.m. the following day. This procedure was repeated until the beans reached a moisture content between 11.2 % and 11.6 %. The beans were then carefully stored in burlap sacks and placed in a storage bin, where they remained for 21 days.

Physicochemical analyses were conducted at the Soil Laboratory and the Food Analysis Laboratory of the IFSULDEMINAS — Campus Inconfidentes. Evaluated variables included moisture content, potential of hydrogen (pH), total titratable acidity (TTA), total soluble solids (°Brix), ether extract (EE), and protein (P), following methodologies of the Association of Official Agricultural Chemists (AOAC) (1990) and the Adolfo Lutz Institute (IAL) (2008). Color

and electrical conductivity (EC) were analyzed according to the methodology of Prete and Abrahão (1995).

Grain color was evaluated using a Konica Minolta portable spectrophotometer (Model CM-2300). The instrument was calibrated with a standard white ceramic calibration plate provided by the manufacturer, using illuminant D65 ($z = 93.6$; $x = 0.3133$; $y = 0.3195$). Readings were obtained using the CIE Lab system, in which L ranges from 0 (black) to 100 (white), indicating luminosity; a^* ranges from $-a^*$ (green) to $+a^*$ (red); and b^* ranges from $-b^*$ (blue) to $+b^*$ (yellow) (Gennadios, Hanna, Kurth, 1997).

After moisture equilibration in storage, the beans were subjected to physical analysis following the Brazilian Normative Instruction (IN) No. 8 of June 11, 2003, which establishes the Technical Regulation of Identity and Quality for the Classification of Processed Green Coffee Beans (Brasil, 2003).

Particle size distribution and the percentage of defects were determined according to IN No. 8/2003 (Brasil, 2003). Granulometric analysis was performed using a set of sieves with variable openings and dimensions, with a total sample of 300 g of defect-free beans. The following sieves were used: sieve 17 (flat beans), sieve 11 (Peaberry beans), sieve 16 (flat beans), sieve 10 (small flat beans), and sieve 15 (small flat beans).

Beverage quality (sensory analysis) was evaluated through cup testing, in which flavor and aroma were assessed. Sensory analyses were conducted at IFSULDEMINAS — Campus Machado by trained and certified Q-Graders using the methodology of the Specialty Coffee Association of America (SCAA) (2009), described by Lingle (2011).

Data were subjected to analysis of variance using the Sisvar software (Ferreira, 2011), and treatment means were compared using

the Scott–Knott clustering test (1974) at the 5 % probability level. Normality was tested using the Lilliefors test in the Genes software. When data did not show normal distribution, transformations were applied. Principal component analysis (PCA) was performed for pest incidence, disease incidence, growth, chlorophyll content, defoliation, dieback, and yield variables. A similarity network was constructed using correlation analysis among variables with the Genes statistical software (Cruz, 2013).

Results and discussion

Data distribution was found not normal for the following variables: chlorophyll, growth, yield, Cercospora leaf spot, soluble solids, electrical conductivity, nitrogen, protein, coordinate a*, Peaberry beans, black-green defect, shell, green beans, sieve size of Peaberry 10 and below, sieve size of flat beans 15 and below, and sensory analysis. The following transformations were applied: $(x \wedge 0.5)$; $(x+0.5) \wedge 0.5$, $(x+1) \wedge 0.5$;

and $\text{Log}(x)$. No significant differences were observed between treatments.

No differences were observed between treatments for defoliation percentage or dieback; however, severe defoliation across treatments may have influenced the high level of dieback observed (Table 3). Damatta *et al.* (2018) reported that climatic factors such as drought and high yield have been empirically correlated with extensive branch mortality. This symptom may also be associated with nutritional deficiency resulting from nitrogen limitation combined with high fruit load, as well as boron and potassium deficiency.

The incidence of coffee leaf miner, coffee leaf rust, Cercospora leaf spot, and the variables growth, chlorophyll content, and yield did not differ significantly between treatments (Table 3).

The intensity of coffee leaf miner attack on coffee plants is influenced by biotic and abiotic factors. According to Androcioli *et al.* (2018), cultivation in association with rubber trees increases the predation of mines by wasps. Thus, environmental variables can directly affect the

Table 3. Mean values for defoliation (DEF - %), shoot dieback (SD - %), coffee leaf miner (CLM - %), coffee leaf rust (CLR - %), Cercospora leaf spot (CLS - %), node growth (NG), chlorophyll content (CHL), and yield in bags ha⁻¹ (YLD) for algae-based biostimulant application at various phenological stages of coffee plants. IFSULDEMINAS – Campus Inconfidentes. Inconfidentes – MG, 2025.

Treatment		DEF	SD	CLM	CLR	CLS	NG	CHL	YLD
Control ³	Control	47.4 ¹ a	76.3 a	6.5 a	19.6 a	6.2 a	3.7 a	36.2 a	84.7 a
Expan.1 ⁴	Post-FF ⁵	43.3 a	48.6 a	11.6 a	21.7 a	7.4 a	5.5 a	51.6 a	70.3 a
Expan.1	Grain filling	53.0 a	34.0 a	7.7 a	19.3 a	7.1 a	3.9 a	54.5 a	77.8 a
Expan.1	Maturation	36.3 a	47.4 a	8.0 a	20.2 a	9.5 a	5.2 a	50.1 a	60.5 a
Expan.1	Expan.2 ⁶	40.5 a	57.6 a	8.3 a	18.1 a	6.8 a	3.7 a	49.7 a	89.8 a
Grain filling	Post-FF	46.4 a	45.1 a	7.7 a	21.4 a	4.4 a	3.5 a	54.2 a	74.8 a
Grain filling	Expan.1	47.4 a	65.2 a	8.6 a	16.3 a	7.7 a	4.1 a	48.5 a	73.0 a
Grain filling	Maturation	41.9 a	63.8 a	6.2 a	18.7 a	5.9 a	4.4 a	49.1 a	109.6 a
CV (%) ²		23.84	38.99	38.28	15.06	41.62	25.75	26.94	23.13

¹Means followed by the same letter in the column do not differ from each other according to the Scott-Knott clustering test (1974) at the 5 % probability level.

²CV: coefficient of variation in percentage; ³Control: Untreated; ⁴Expan.1: Expansion 1; ⁵Post-FF.: Post-first flowering; ⁶Expan.2: Expansion 2.

Source: authors (2025).

activity of phytophagous insects, resulting in increased populations in hot, dry, and unshaded regions (Reis *et al.*, 2000; Leite *et al.*, 2020). The economic injury level of this pest is reached when 14.65 % of the leaves sampled from the middle third of the plant are mined (Picanço Filho *et al.*, 2024). In the present study, values from 6.25 to 11.61 % of mined leaves were recorded, which are considered below the economic injury level.

Castillo *et al.* (2022) emphasized that, for any coffee cultivar, nutrient availability is essential for growth and for the immune system, reducing the rate of fungal spread; due to their nutritional composition, algae-based biostimulants may provide satisfactory management of coffee leaf rust.

Delgado-Baquerizo *et al.* (2020) and Chaloner, Gurr, and Bebbler (2021) reported that climatic factors such as relative humidity and leaf wetness are key determinants for disease development. Among these diseases, *Cercospora* leaf spot is noteworthy, as it is favored by leaf wetness. In regions with conditions conducive to *Cercospora* leaf spot development, losses may reach up to 30 % of production, causing a significant impact on yield (Zambolim, 1999).

According to Pascuti *et al.* (2023), in a study conducted with different doses of Cerrado Mineiro coffee crops during the 2019/2020 season using extracts of *Ascophyllum nodosum*, no significant differences were observed between treatments for yield or plant growth at the end of the cycle.

According to Long (2006), identifying the effects of products with biostimulant action, such as algae-based biostimulant, is easier under stress conditions. In environments favorable to plant development, application of these products is often unnecessary, making their effects less evident in crops. This may explain the lack of significant effects on coffee plants for the variables analyzed, as the crop was managed

appropriately during the study period and meteorological conditions were also favorable (Figure 1).

No significant differences were observed among treatments for pH, total titratable acidity (TTA), total soluble solids (TSS), electrical conductivity (EC), ether extract (EE), protein content, or color coordinates L*, a*, and b* (Table 4). During the physical, chemical, and microbiological analyses of coffee fruits, some methodological adaptations were required due to variations in the equipment used (including brand and calibration) and differences in materials, such as filter paper type. These modifications may have influenced the results obtained, generating discrepancies relative to values reported in the literature.

Certainly, for the pH variable, the lack of significant results is a consequence of adopting the same post-harvest management for all treatments. According to Silva *et al.* (2019), acidity is a crucial indicator of coffee quality, reflecting the presence of various organic acids that influence the beverage's sensory characteristics. Moreover, its variation is directly associated with fruit maturation stage, region of origin, drying method, among other factors.

The influence of ether extract on beverage quality in Arabica coffee depends on the production region, but levels are generally reported to range from 12 % to 16 % (Mazzafera *et al.*, 1998; Folstar, 1985; Martinez *et al.*, 2014); the values found in this study were below this range, largely due to adaptations made to the methodology used. Campos *et al.* (2022) found that different coffee processing methods strongly influence protein quality and, consequently, beverage aroma.

No significant differences were observed among treatments for the physical classification of coffee—defect sorting, sieve size distribution, and sensory analysis—indicating no influence of

Table 4. Mean values for hydrogen potential (pH), total titratable acidity as a percentage (TTA - %), total soluble solids as a percentage (TSS - %), electrical conductivity (EC - $\mu\text{S cm}^{-1} \text{ g}^{-1}$ sample), ether extract as a percentage (EE - %), protein as a percentage (PRO - %), and colorimetric coordinates L, a*, and b* for algae application at various phenological stages of coffee plants. IFSULDEMINAS – Campus Inconfidentes. Inconfidentes – MG, 2025.

Treatment		pH	TTA	TSS	EC	EE	PRO	L	a*	b*
Control ³	Control	6.0 ¹ a	11.8 a	1.1 a	2.7 a	4.3 a	14.6 a	52.6 a	3.1 a	22.5 a
Expan.1 ⁴	Post-FF ⁵	6.0 a	12.0 a	1.1 a	2.9 a	4.6 a	14.4 a	53.4 a	2.9 a	22.2 a
Expan.1	Grain filling	6.0 a	12.3 a	1.1 a	3.1 a	4.5 a	11.6 a	55.3 a	2.7 a	23.0 a
Expan.1	Maturation	5.9 a	12.6 a	1.1 a	3.1 a	4.8 a	12.3 a	54.6 a	3.0 a	23.1 a
Expan.1	Expan.2 ⁶	5.9 a	9.5 a	1.1 a	3.2 a	4.7 a	12.0 a	54.9 a	3.5 a	23.4 a
Grain filling	Post-FF	6.0 a	9.6 a	1.1 a	3.3 a	4.3 a	11.9 a	55.0 a	3.2 a	22.9 a
Grain filling	Expan.1	6.0 a	12.3 a	1.1 a	3.5 a	4.4 a	11.2 a	55.0 a	3.3 a	23.4 a
Grain filling	Maturation	6.0 a	11.6 a	1.1 a	10.6 a	3.7 a	13.3 a	55.4 a	10.6 a	22.3 a
CV (%) ²		0.98	15.97	9.66	28.58	14.95	13.18	7.07	112.63	5.79

¹Means followed by the same letter in the column do not differ by the Scott-Knott test (1974) at 5 % probability.

²CV: coefficient of variation in percentage; ³Control: Untreated; ⁴Expan.1: Expansion 1; ⁵Post-FF.: Post-first flowering; ⁶Expan.2: Expansion 2.

Source: authors (2025).

algae application (Table 5). The initial hypothesis was that algae-based biostimulant could affect coffee bean quality, as more appropriate crop management practices are essential for reducing defects and increasing bean size (screen size). This is supported by Kurniawan *et al.* (2024), who reported that balanced fertilization combining chemical and organic fertilizers increased coffee bean weight.

Even with the high defect sorting rate and disease incidence, which were influenced by meteorological conditions, the beans had excellent sieve classification and high sensory quality. This resulted in specialty coffee scores above 80, demonstrating that despite phytosanitary challenges, the final product quality remained high.

According to the Specialty Coffee Association of America (SCAA) (2009), coffee is considered specialty when it scores from 80 to 100 points

based on the association's criteria. Thus, although treatments did not differ from one another, all reached the specialty grade, with scores ranging from 81.50 to 82.75 points.

In the principal component analysis (PCA) (Figure 2), the statistical result explained 63.39 % of the total variance. The treatments most associated with yield were algae applications at stages T8 (maturation and grain filling), T7 (grain filling and expansion 1), T5 (expansion 1 and expansion 2), and the control.

Greater defoliation and shoot dieback were correlated with higher crop yield. According to Khalajabadi, Poveda, and Sáens (2025), nutrient dynamics and growth of coffee plants differ markedly between flowering and yield stages. These authors observed greater defoliation after anthesis, noting that fewer leaves per node with fruits indicates that most defoliation occurred during the reproductive phase. In addition, nutrient

Table 5. Physical classification of coffee for the variables percentage of defect sorting, sieve size distribution for screen 17 (flat beans), screen 11 (Peaberry beans), screen 16 (flat beans), screen 10 (small Peaberry beans), screen 15 (small flat beans), and sensory analysis (score) for algae application at various phenological stages of coffee plants. IFSULDEMINAS – Campus Inconfidentes. Inconfidentes – MG, 2025.

Treatment		Defect sorting	S17 flat	S11 Peaberry	S16 flat	S10 small Peaberry	S15 small flat	Sensory analysis
Control ³	Control	33.38 ¹ a	58.62 a	7.63 a	22.39 a	3.06 a	8.38 a	82.08 a
Expan.1 ⁴	Post-FF ⁵	34.83 a	58.62 a	8.58 a	21.82 a	4.13 a	7.33 a	82.33 a
Expan.1	Grain filling	30.91 a	64.69 a	7.14 a	19.48 a	2.74 a	6.39 a	82.75 a
Expan.1	Maturation	31.56 a	57.82 a	9.71 a	19.88 a	2.74 a	8.74 a	81.58 a
Expan.1	Expan.2 ⁶	34.35 a	59.40 a	8.34 a	22.47 a	4.16 a	6.37 a	81.50 a
Grain filling	Post-FF	31.32 a	54.22 a	9.27 a	24.32 a	5.05 a	8.11 a	82.53 a
Grain filling	Expan.1	32.53 a	67.62 a	6.22 a	18.45 a	1.97 a	5.85 a	82.17 a
Grain filling	Maturation	29.84 a	65.95 a	7.38 a	19.98 a	2.49 a	5.18 a	82.17 a
CV (%) ²		19.73	15.83	36.32	23.05	59.75	30.51	1.56

¹Means followed by the same letter in the column do not differ from each other according to the Scott-Knott clustering test (1974) at the 5 % probability level.

²CV: coefficient of variation in percentage; ³Control: Untreated; ⁴Expan.1: Expansion 1; ⁵Post-FF.: Post-first flowering; ⁶Expan.2: Expansion 2.

Source: authors (2025).

concentrations in branches and leaves were lower at harvest than at anthesis due to mobilization of photosynthates. These findings highlight the importance of well-nourished branches and leaves to meet both vegetative and reproductive demands, thereby reducing shoot dieback.

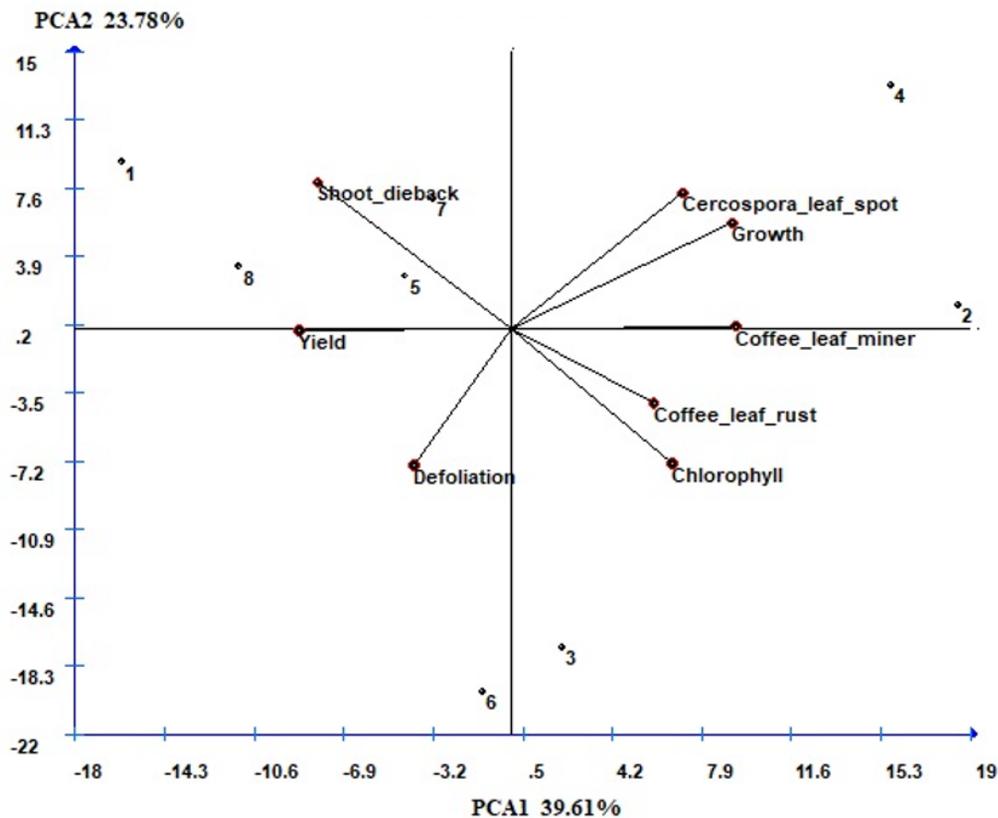
Regarding the incidence of coffee leaf miner, coffee leaf rust, and *Cercospora* leaf spot, the data were associated with greater vegetative growth and lower yield (Figure 2), represented by treatments 2 (Expansion 1 and post-first flowering), 3 (Expansion 1 and grain filling), and 4 (Expansion 1 and maturation). However, treatments with higher yield also showed greater defoliation, which hindered monitoring of the same leaves throughout the evaluation period and therefore likely underestimated pest and disease incidence. Since coffee has a biennial phenological cycle, plants with greater node growth tend to have lower productivity, a pattern observed among treatments 4, 3, and 2 (Figure 2). PCA enabled identification of

trends not detected by conventional parametric analyses, indicating phenological stages more favorable for algae application with effects on coffee growth and yield.

A similarity network was used to evaluate relationships among variables. The association measure ranged from -1 to $+1$ (Figure 3); values closer to these extremes indicate stronger associations. Positive relationships indicate that both variables increase simultaneously, whereas negative relationships indicate that one variable decreases as the other increases. Red lines represent negative correlations and green lines represent positive correlations, with thicker lines indicating stronger relationships. Only correlations with weight greater than 0.8 were considered.

Negative correlations were identified between shoot dieback and chlorophyll, growth and moisture, pH and electrical conductivity, pH and color coordinate b^* , nitrogen and color

Figure 2. Principal component analysis for growth and yield variables of coffee plants subjected to algae application at various phenological stages. IFSULDEMINAS – Campus Inconfidentes. Inconfidentes – MG, 2025.



Source: authors (2025).

coordinate b^* , protein and color coordinate b^* , growth and shell core defect, black-green defects and defect-free beans, defect-free beans and defect sorting, screen 17 and screen 11, screen 17 and screen 16, screen 17 and screen 10, and screen 17 and screen 15. Positive correlations were observed between yield and total soluble solids, nitrogen and protein, yield and color coordinate a^* , electrical conductivity and color coordinate b^* , moisture and shell core defect, black-green defects and defect sorting, and screen 11 and screen 10.

It is important to emphasize that these associations are not necessarily related to the applied treatments, as numerous analyses were conducted. For future studies, it will not be necessary to evaluate the “black-green” defect and

“defect sorting” variables simultaneously, as both show a strong positive relationship and therefore tend to increase together. This simplification will reduce costs and effort, requiring evaluation of only one of these variables.

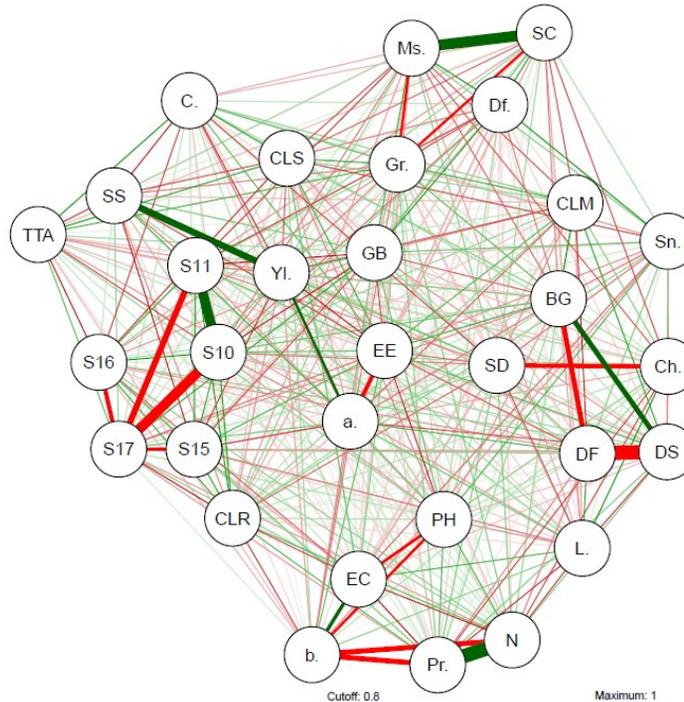
Conclusion

Application of the freshwater algae-based biostimulant at various phenological stages does not influence the growth or yield of Arabica coffee.

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Figure 3. Similarity network for growth, yield, and physicochemical quality variables of coffee subjected to algae application at various phenological stages. IFSULDEMINAS – Campus Inconfidentes. Inconfidentes – MG, 2025.



Related variables: total titratable acidity (TTA); soluble solids (SS); electrical conductivity (EC); moisture (Moist.); shell core defect (SC); screen 16 (S16); screen 11 (S11); Cercospora leaf spot (CLS); screen 17 (S17); screen 10 (S10); yield (Yld.); green beans (GB); growth (Gr.); defoliation (Def.); screen 15 (S15); coffee leaf rust (CLR); color coordinate a* (a*); ether extract (EE); color coordinate b* (b*); hydrogen potential (pH); shoot dieback (SD); black-green beans (BG); coffee leaf miner (CLM); protein (Prot.); nitrogen (N); color coordinate L* (L*); defect-free beans (DF); defect sorting (DS); chlorophyll (Chl.); and sensory analysis (Sn.).

**Significant at 1 %; *cutoff value for correlation = 0.8.

Source: authors (2025).

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