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Salinity stress in sugarcane: genotypic variability and biostimulant-driven mitigation

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ABSTRACT

Salinity and soil sodicity are major abiotic constraints limiting sugarcane (*Saccharum* spp.) establishment and biomass accumulation, particularly in irrigated regions. This study aimed to integrate the evaluation of genotypic variability for sodicity tolerance with the assessment of a seaweed-based biostimulant strategy during early sugarcane development. Under greenhouse conditions in Minas Gerais, Brazil, forty-three sugarcane genotypes were screened for sodicity tolerance using a completely randomized design in a 43 × 2 factorial arrangement (genotypes × soil salinity levels), with tolerance quantified using the sodicity tolerance index (STI, %) based on shoot dry mass. Based on this screening, two genotypes with contrasting responses, the tolerant H. Kawandang (*Erianthus arundinaceus*) and the susceptible cultivar SP80-1842 were selected for a second phase conducted in a completely randomized design in a 2 × 5 factorial arrangement, combining two NaCl concentrations (control and 100 mM NaCl) with five doses of an *Ascophyllum nodosum* based biostimulant (0, 1.25, 2.5, 5.0 and 10.0 mL L^{-1}). Plant height, shoot dry mass, and STI were evaluated. In the screening phase (first experiment), wide genotypic variability was observed, with STI values ranging from near zero to 78.33%. H. Kawandang and the energy cane hybrid Vertix 5 showed greater tolerance compared with the other evaluated genotypes. In the second experimental phase, biostimulant application promoted early plant growth and increased STI under saline conditions, with the most consistent responses observed at a dose of 5.0 mL L^{-1}.

Keywords: *Saccharum* spp., Sodicity tolerance, Abiotic stress, Energy cane, Soil salinity.

Estresse salino em cana-de-açúcar: variabilidade genotípica e mitigação por biosestimulante

RESUMO

A salinidade e a sodicidade do solo são importantes estresses abióticos que limitam o estabelecimento e o acúmulo de biomassa da cana-de-açúcar (*Saccharum* spp.), especialmente em regiões irrigadas. Este estudo teve como objetivo integrar a avaliação da variabilidade genotípica quanto à tolerância à sodicidade com a análise do uso de um bioestimulante à base de algas marinhas no desenvolvimento inicial da cultura. Em condições de casa de vegetação, em Minas Gerais, Brasil, quarenta e três genótipos de cana-de-açúcar foram avaliados quanto à tolerância à sodicidade em delineamento inteiramente casualizado, em esquema fatorial 43 × 2 (genótipos × níveis de salinidade do solo), utilizando-se o índice de tolerância à sodicidade (STI, %) baseado na massa seca da parte aérea. Com base nesse rastreamento, dois genótipos com respostas contrastantes H. Kawandang (*Erianthus arundinaceus*) e a cultivar suscetível SP80-1842 foram selecionados para uma segunda fase, conduzida em delineamento inteiramente casualizado, em esquema fatorial 2 × 5, combinando duas concentrações de NaCl (controle e 100 mM) e cinco doses de um bioestimulante à base de *Ascophyllum nodosum* (0; 1,25; 2,5; 5,0 e 10,0 mL L^{-1}). Avaliaram-se altura de plantas, massa seca da parte aérea e STI. Observou-se ampla variabilidade genotípica na fase de triagem (primeiro experimento), com valores de STI variando de próximos a zero até 78,33%. H. Kawandang e o híbrido de cana-energia Vertix 5 apresentaram maior tolerância em relação aos demais genótipos avaliados. Na segunda fase experimental, a aplicação do bioestimulante favoreceu o crescimento inicial e aumentou o STI, com respostas mais consistentes na dose de 5,0 mL L^{-1} sob condição salina.

Palavras-chave: *Saccharum* spp.*;* Tolerância à sodicidade, Estresse abiótico, Cana-energia, Salinidade do solo.

1. Introduction

Soil sodicity, characterized by an excess of sodium ions (Na^+), causes osmotic and ionic stress in plants, which reduces water uptake and leads to physiological damage to plant cells (Watanabe et al., 2020). This excess of sodium ions also impairs photosynthetic activity by limiting essential enzymes and reducing CO_2 diffusion in the cytosol (Pan et al., 2021). High Na^+ concentrations compromise cell membrane integrity and disrupt vascular tissue functionality, impairing water and nutrient transport and directly limiting plant growth (Saleem et al., 2024).

Increased soil salinity raises electrical conductivity and can give rise to reactive oxygen species (ROS). These ROS oxidize cellular tissues, lipids, proteins, and nucleic acids essential for plant growth, leading to chlorosis, wilting, necrosis, and senescence (Genetu and Getahum, 2024; Rao et al., 2021). In addition to these oxidative effects, an excess of sodium ions (Na^+) in the soil solution compromises mineral nutrition. The ionic similarity of Na^+ with potassium (K^+) causes antagonistic interactions that reduce K^+ uptake and disrupt key metabolic processes. This Na^+–K^+ antagonism has been well-established in plant mineral nutrition and documented in classical studies (Malavolta, 2006), and it ultimately results in growth impairment and yield reduction (Dhansu et al., 2022).

Sugarcane (*Saccharum* spp.), a major crop of the *Poaceae* family with high economic importance in tropical and subtropical regions, is classified as a glycophyte and is therefore sensitive to salinity stress (Mahadevaiah et al., 2023). This sensitivity can significantly impair the plant at various stages of its development. Depending on the genotype, yield losses may exceed 40% when soil electrical conductivity reaches 8 dS m^{-1} (Morais et al., 2022). However, due to high genetic variability, sugarcane genotypes may exhibit contrasting responses to salinity, especially among commercial cultivars that were not specifically selected for sodium tolerance (Chiconato et al., 2019; Meena et al., 2020; Morais et al., 2022).

In this context, varietal selection remains a key strategy for improving sugarcane performance under saline conditions. This approach can be further enhanced by complementary management practices, such as the application of biostimulants (Chiconato et al., 2019; Meena et al., 2020). Among these, Ascophyllum nodosum (brown seaweed) extract has gained attention due to its ability to stimulate shoot and root development through phytohormone modulation and activation of stress-responsive genes, which promote osmoprotectant accumulation and increase salinity tolerance (Li et al., 2022).

Therefore, evaluating sugarcane genotypic responses to salinity, both apart from and in combination with biostimulant application, can support both crop management strategies and breeding programs targeting saline environments. Within this context, the present study tested two hypotheses: (i) sugarcane genotypes differ in their tolerance to salinity stress, and (ii) biostimulant application enhances early plant development under saline conditions. Accordingly, this study aimed to screen 43 sugarcane genotypes for tolerance to saline soil conditions and evaluate the effects of different doses of A. nodosum biostimulant on two selected genotypes with contrasting levels of salinity tolerance.

2. Material and Methods

The study was conducted under greenhouse conditions at the Universidade Federal de Lavras (UFLA) in Minas Gerais, Brazil, and comprised two complementary experimental phases carried out sequentially. The first phase was performed at the Centro de Desenvolvimento e Transferência de Tecnologia (Center for Technology Development and Transfer) - CDTT, Department of Agriculture, in Ijaci, Minas Gerais, Brazil (21°09′49″ S, 44°54′59″ W; 889 m a.s.l.). The second phase was conducted at the field crops sector of the Department of Agriculture/ESALQ at UFLA, in Lavras, Minas Gerais, Brazil (21°14′31.87″ S, 44°59′55″ W; 919 m a.s.l.). The climate at both locations is classified as Cwa according to the Köppen classification system, as described by Alvares et al. (2013). All experiments were carried out under controlled greenhouse conditions, with air temperature ranging from 25 to 28 °C and relative humidity maintained between 60% and 80% throughout the experimental period.

Stalks from forty-three 8- to 10-month-old sugarcane genotypes were identified, selected, and collected. The evaluated material included three species: ARCHI (*S. sinense*), Caiana (*S. officinarum*), and H. Kawandang (*Erianthus arundinaceus*). In addition, 5 commercial energy cane cultivars (Vertix 2, 3, 5, 7, and 10) and 35 commercial sugarcane cultivars were included. The complete list of all 43 genotypes is presented in Table 1.

The 43 genotypes were selected from the germplasm collection maintained at the CDTT, which includes wild relatives, energy cane hybrids, and elite commercial sugarcane cultivars, thereby providing for exploration of broad genetic variability for sodicity tolerance.

Table 1. Sugarcane genotypes evaluated in the sodicity tolerance screening experiment.

No.	Genotype	No.	Genotype	No.	Genotype
1	CB45-3	16	RB72454	31	SP79-1011
2	CO413	17	RB739735	32	SP80-1816
3	CTC 1	18	RB835054	33	SP80-1842
4	CTC 2	19	RB835486	34	SP81-3250
5	CTC 3	20	RB845210	35	SP89-1115
6	CTC 4	21	RB855036	Energy cane cultivars	
7	CTC 5	22	RB855113	36	Vertix 2
8	CTC 14	23	RB867515	37	Vertix 3
9	CTC 15	24	RB98710	38	Vertix 5
10	CTC 9001	25	RB987935	39	Vertix 7
11	CTC 9002	26	RB988082	40	Vertix 10
12	CTC 9003	27	RB002504	Species	
13	IAC86-2210	28	RB036066	41	ARCHI
14	IAC86-2480	29	RB036091	42	Caiana-Verde
15	IAC87-3396	30	SP77-5181	43	H. Kawandang

After collection, the stalks were sectioned into 5-cm internodes and planted in trays with 0.135 dm^3 cell volume, filled with a 2:1 mixture of soil and sand. Prior to planting, the soil was chemically analyzed and amended, following the methodological recommendations proposed by Resende et al. (2012) for greenhouse agronomic evaluations.

The experiment followed a completely randomized design (CRD) in a 43 × 2 factorial arrangement, with the first factor consisting of the 43 genotypes and the second factor consisting of two sodium chloride (NaCl) concentrations: control [naturally occurring soil concentration; electrical conductivity (EC) = 0.083 dS m^{-1}] and a salinity treatment (T1) [soil amended with 100 mM NaCl; EC = 7.2 dS m^{-1}]. The salinity level adopted for T1 was defined based on previously established methodologies for salinity screening in sugarcane, in which NaCl enrichment resulting in EC values around 7.0 dS m^{-1} was shown to be effective for discriminating genotypic responses without completely inhibiting plant establishment (Silva et al., 2022). To ensure uniform salinity conditions, the NaCl was thoroughly homogenized in the soil using a concrete mixer prior to filling the trays. Each treatment was replicated four times (n = 4), for a total of 344 plants.

Plants were irrigated manually, maintaining the soil at field capacity. In cases of excessive irrigation, the leachate collected in drainage containers was returned to the respective cells to avoid salt loss and ensure consistent salinity levels throughout the experimental period.

At 33 days after planting (DAP), the plants were harvested. Roots and stalk pieces were separated and discarded due to their low weight and high coefficient of variation (C.V.). Therefore, only the shoots were analyzed, as they showed consistent mass values and lower experimental error, making them more suitable for calculating the tolerance indices in this study. The shoots were oven-dried at 70 °C for 72 h and then weighed on an analytical balance to determine shoot dry mass (SDM, g). The sodicity tolerance index (STI, %) was calculated using Equation 1.

$$STI(\%)=(\text{SDM under sodium treatment}/\text{SDM in control treatment})\times 100. \quad (1)$$

Based on the wide genetic variability and the responses to salinity observed in the sodicity screening phase, which identified five groups of genotypes with distinct responses to salinity, two genotypes with contrasting tolerance levels were selected for the subsequent phase: H. Kawandang (tolerant) and SP80-1842 (susceptible).

For the second phase, a completely randomized design was adopted for each genotype, in a 2 × 5 factorial arrangement. The first factor consisted of two NaCl concentrations: control (naturally occurring soil content) and the saline soil treatment (T1 - soil amended with 100 mM NaCl), while the second factor consisted of different doses of the biostimulant Roadster® (*A. nodosum*) [0, 1.25, 2.5, 5.0 and 10.0 mL L^{-1}]. Five plants were evaluated per treatment for each genotype (H. Kawandang; tolerant and SP80-1842; susceptible), for a total of 60 plants per genotype.

Soil salinity was amended with sodium chloride (NaCl), which was homogenized with the soil using a concrete mixer prior to placing it in plant tubes. This soil amendment procedure resulted in EC values comparable to those adopted in the sodicity tolerance screening phase, ensuring consistency between experimental phases. After plant harvest, the EC of the soil solution was determined using a conductivity meter; mean values were 1.65 dS m^{-1} for the control soil and 7.1 dS m^{-1} for the saline treatment. According to Richards (1954), soils with EC values above 4 dS m^{-1} are classified as saline.

Selected stalks were sectioned into 5-cm mini-stems and submerged in an aqueous solution containing the different doses of biostimulants for one minute. Subsequently, the mini-stems were planted in 3-dm^3 tubes (citropots) filled with clay soil. The soil was classified as a Latossolo Vermelho-Amarelo with a clayey texture, according to the Brazilian Soil Classification System (SiBCS) (Santos et al., 2018), corresponding to a Typic Hapludox according to the USDA Soil Taxonomy (Soil Survey Staff, 2022). The chemical properties of the soil in the 0–20 cm layer are shown in Table 2.

Table 2. Chemical properties of the soil collected from the 0–20 cm layer prior to experiment establishment.

Property	Value	Unit	Property	Value	Unit
pH ($CaCl_2$)	5.8	—	Sum of bases (SB)	4.22	cmolc dm^{-3}
pH (SMP)	6.98	—	Effective CEC [CEC(t)]	75.5	mmolc dm^{-3}
Organic matter (OM)	17	g dm^{-3}	Potential CEC [CEC(T)]	90.5	mmolc dm^{-3}
Phosphorus (P, Mehlich-1)	8	mg dm^{-3}	Base saturation (V)	71	%
Potassium (K^+)	0.5	mmolc dm^{-3}	Aluminum saturation (m)	1.0	%
Potential acidity ($H^+ + Al^{3+}$)	15.0	mmolc dm^{-3}	Zinc (Zn)	0.4	mg dm^{-3}
Exchangeable aluminum (Al^{3+})	0.755	mmolc dm^{-3}	Manganese (Mn)	22.2	mg dm^{-3}
Calcium (Ca^{2+})	32.0	mmolc dm^{-3}	Copper (Cu)	3.0	mg dm^{-3}
Magnesium (Mg^{2+})	5.0	mmolc dm^{-3}	Boron (B)	<0.12	mg dm^{-3}
Sodium (Na^+)	38	mmolc dm^{-3}	Sulfur (S)	<1.0	mg dm^{-3}

Footnote: pH was determined in $CaCl_2$; organic matter (OM) is expressed in g dm^{-3}. S–SO_4 $^{2-}$, B, Cu, Fe, Mn, and Zn are expressed in mg dm^{-3}. Potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), potential acidity ($H^+ + Al^{3+}$), exchangeable aluminum (Al^{3+}), sodium (Na^+), sum of bases (SB), and cation exchange capacity (CEC) are expressed in mmolc dm^{-3}. Copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) were extracted using the DTPA method.

At 60 days after planting (DAP), final emergence percentage was calculated as the ratio of the total number of emerged seedlings and the total number of planted buds. Seedling development was assessed by measuring plant height (from soil level to the dewlap of the +1 leaf). Plants were then cut at the stem collar, and the shoots were dried in a forced-air circulation oven at 70 °C for 72 h and weighed to determine shoot dry mass (SDM, g). Using the SDM data, the sodicity tolerance index (STI, %) was calculated according to Equation 1.

Data from the sodicity screening phase were subjected to an analysis of variance (ANOVA), and when significant, the means were compared using the Scott–Knott test (α = 5%). To meet the ANOVA assumptions of normality and homoscedasticity, the sodicity tolerance index (STI, %) data were transformed using $\sqrt{(x + 0.5)}$; however, the original (untransformed) means are presented in the figures for clarity. Data from the biostimulant evaluation phase were also subjected to ANOVA. The effects of biostimulant doses were analyzed using polynomial regression, considering linear and quadratic models, as well as the interactions between doses and sodium levels. All statistical analyses were performed using the SISVAR® statistical software (Ferreira, 2019).

3. Results and Discussion

Significant genotypic variability was observed among the 43 sugarcane genotypes evaluated for the sodicity tolerance index (STI) (Figure 1). The STI values ranged from near zero to 78.33%, demonstrating a wide spectrum of tolerance among the materials under saline conditions (EC = 7.2 dS m^{-1}). According to the Scott–Knott test ($p \leq 0.05$), H. Kawandang (*Erianthus arundinaceus*) and Vertix 5 formed the most tolerant statistical groups, with STI values above 50% (Figure 1). However, H. Kawandang (78.33%) was statistically superior to Vertix 5 (58.75%), confirming its markedly higher tolerance to soil salinity. These genotypes maintained shoot dry mass production close to that of the control treatment (naturally occurring soil salinity, EC = 1.65 dS m^{-1}), as reflected by the STI values (Figure 1). This indicates a greater capacity to sustain physiological activity under osmotic and ionic stress conditions (Chiconato et al., 2019; Rao et al., 2021; Dhansu et al., 2022).

The outstanding performance of H. Kawandang in terms of the sodicity tolerance index (STI, %) (Figure 1) confirms the recognized hardiness of *Erianthus* species. These materials exhibit robust anatomical and physiological traits, such as a dense and lignified root system and compact cortical parenchyma, which enhance mechanical resistance and facilitate selective ion transport (Melo et al., 2018; Vignesh et al., 2021). These traits, together with mechanisms related to osmotic adjustment and antioxidant enzyme activity described in the literature, were not directly evaluated in the present study, but likely help explain the higher salinity tolerance of *E. arundinaceus* compared with *Saccharum* genotypes.

The energy cane hybrid Vertix 5 also showed high STI values (58.75%) (Figure 1), confirming its superior tolerance relative to most of the other genotypes evaluated and its potential for cultivation in sodic environments. This cultivar incorporates genetic contributions from *Saccharum spontaneum*, a wild species widely recognized as a source of tolerance to abiotic stresses, including salinity and drought. Studies indicate that the presence of *S. spontaneum* genetic material is associated with improved ion homeostasis and maintenance of photosynthetic efficiency under salinity stress conditions, contributing to better plant performance in adverse environments (Cruz et al., 2021; Vignesh et al., 2021).

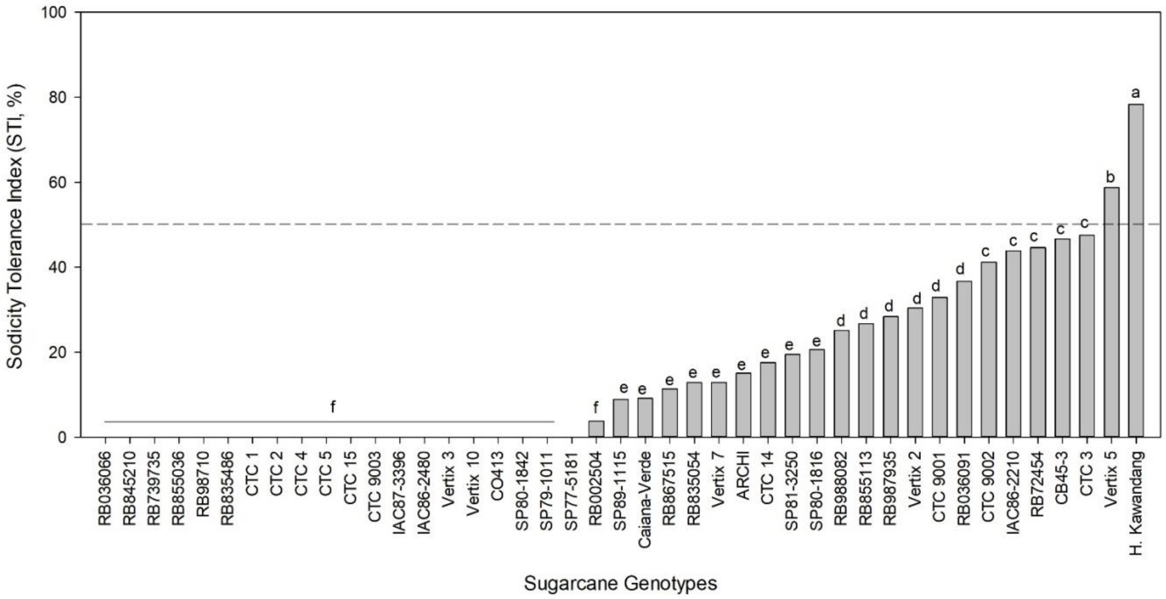

Figure 1. Sodicity tolerance index (STI) of 43 sugarcane genotypes at 33 days after planting (DAP).

Means followed by the same letter do not differ according to the Scott-Knott test ($p \leq 0.05$). C.V. (%) = 37.1 and overall mean = 15.6. The dashed horizontal line represents the 50% STI reference threshold used for genotype classification.

In contrast, the majority of the commercial sugarcane cultivars exhibited low STI values, below 40 %, indicating high sensitivity to sodicity (Figure 1). Similar trends have been reported in the literature, whereby salinity stress reduced growth, yield, and biomass accumulation in conventional sugarcane cultivars (Chiconato et al., 2019; Morais et al., 2022). These findings confirming that elevated soil salinity negatively impacts key agronomic traits highlight that the current genetic base of commercial sugarcane remains poorly adapted to saline and sodic soils.

Overall, the wide variation detected for STI confirms the existence of exploitable genetic diversity for salinity tolerance within the sugarcane germplasm (Figure 1). The genotypes identified as tolerant, H. Kawandang and Vertix 5, represent valuable genetic resources for breeding programs focused on improving sugarcane adaptation to marginal environments or for developing energy cane cultivars for bioenergy production systems.

The selection of plant material for the subsequent biostimulant study (Experiment II) was based on the sodicity tolerance results obtained in Experiment I (Figure 1). The species H. Kawandang (tolerant; STI = 78.33%) and the commercial cultivar SP80-1842 (susceptible; STI < 10%) were selected to represent contrasting genotypic responses to salinity stress.

In H. Kawandang, the application of *Ascophyllum nodosum* biostimulant significantly influenced plant height, shoot dry mass (SDM), and the sodicity tolerance index (STI, %) (Figure 2). For plant height, no significant interaction between soil salinity and biostimulant dose was observed; therefore, regression analysis was performed considering only the effect of biostimulant doses (Figure 2A). Although salinity did not significantly affect plant height (mean values of 4.48 cm under salt stress and 4.95 cm under the control), a quadratic response to increasing biostimulant doses was observed, with the maximum technical response estimated at approximately 4.37 mL L^{-1}. Conversely, a significant interaction between soil salinity and biostimulant dose was detected for SDM, indicating that plant response varied according to stress intensity. Under saline conditions, SDM showed a significant quadratic fit, with the maximum value (0.78 g) estimated at 5.04 mL L^{-1} (Figure 2B). Similarly, the STI exhibited a quadratic response under saline conditions, reaching a maximum estimated value of 99.13% at 5.05 mL L^{-1} (Figure 2C).

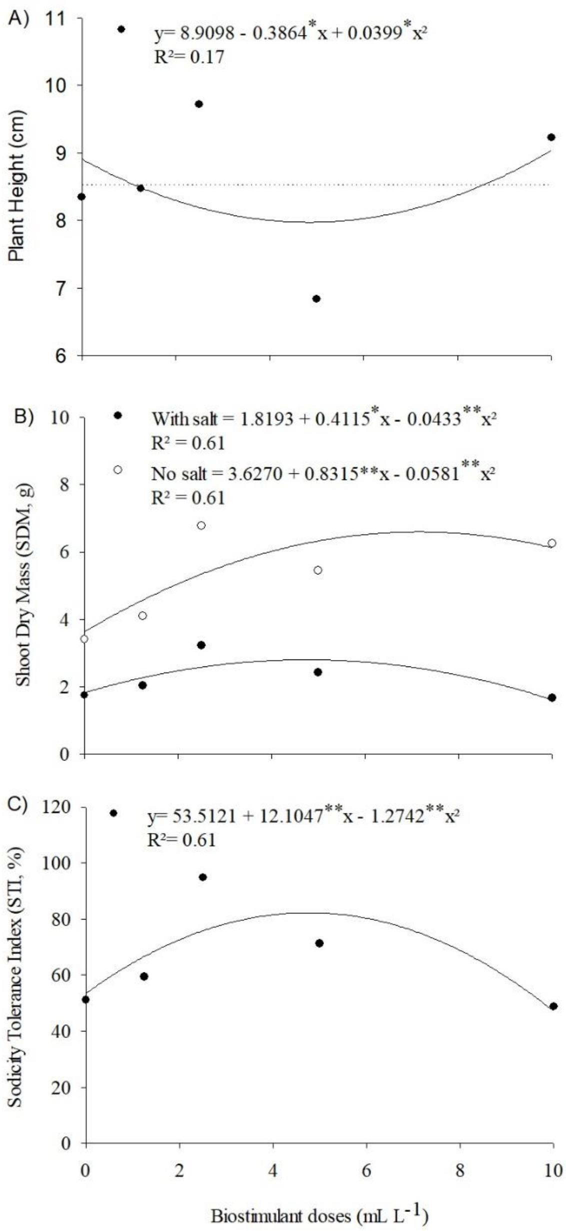

Figure 2. SP80-1842 plant response to biostimulant doses under saline conditions for (A) plant height (cm), (B) shoot dry mass (SDM, g), and (C) sodicity tolerance index (STI, %).

** and * denote significance at the 1% and 5% probability levels, respectively, by the F test. The dashed horizontal line in (A) represents the mean.

Positive effects from the biostimulant Ascophyllum nodosum were observed in the present study for doses applied to both genotypes under saline conditions, particularly at the dose of 5.0 mL L^{-1} (Figures 2B–C and 3B–C). Under these conditions, the biostimulant enhanced shoot dry mass (SDM) and the sodicity tolerance index (STI), especially in the tolerant genotype H. Kawandang.

These effects can be attributed to the complex mixture of bioactive compounds present in A. nodosum, which include alginates, laminarins, phenolic compounds, and natural phytohormones such as auxins, cytokinins, and gibberellins (Li et al., 2022). Such compounds have been associated with improved osmotic adjustment, stimulation of antioxidant defense systems, and better ion homeostasis under salinity stress (González-Pérez et al., 2022; Pienaar et al., 2025).

Studies conducted under saline and sodic conditions demonstrate that these physiological adjustments are associated with reduced oxidative damage, greater membrane stability, and improved ion homeostasis, particularly through maintenance of a higher K^+/Na^+ ratio (Pan et al., 2021; Rao et al., 2021; Morais et al., 2022). Although these mechanisms were not directly quantified in the present study, the growth responses observed here are consistent with the effects reported for seaweed-based biostimulants applied on sugarcane and other crops under salt stress conditions (Li et al., 2022; Jacomassi et al., 2022; Pienaar et al., 2025).

Notably, the magnitude of response under saline conditions was greater in H. Kawandang than in SP80-1842 (Figures 2 and 3). Although the experimental design did not include statistical comparison between genotypes, the tolerant genotype exhibited higher absolute SDM and STI values and a more consistent quadratic model fit in response to biostimulant doses. This suggests that the effectiveness of biostimulants depends on the intrinsic physiological capacity of the genotype to cope with stress.

Specifically in sugarcane, Jacomassi et al. (2022) reported that the application of seaweed extract mitigated the negative effects of drought stress, as shown by improved shoot biomass accumulation and physiological performance. Similarly, Chen et al. (2021) demonstrated that seaweed-based products enhanced cane growth and physiological activity under field conditions. Although the magnitude of increase varied according to environmental conditions and genotype, these studies reinforce that seaweed extracts function as metabolic enhancers, potentiating plant defense mechanisms rather than directly eliminating stress factors.

Furthermore, the application of *A. nodosum* at 5.0 mL L^{-1} increased plant height under saline conditions, particularly in H. Kawandang (Figure 2A), while a less pronounced response was observed in SP80-1842 (Figure 3A). This improvement reflects better growth recovery under osmotic restriction. These findings are consistent with Li et al. (2022), who demonstrated through a meta-analysis that seaweed-based products tend to lead to greater agronomic efficiency under salinity stress conditions. The optimal dose identified in this study (around 5 mL L^{-1}), as indicated by the quadratic regressions for SDM and STI in H. Kawandang (Figures 2B and 2C) and SP80-1842 (Figures 3B and 3C), suggests that doses close to 5.0 mL L^{-1} maximize beneficial effects, whereas higher doses may result in diminished responses, possibly due to metabolic or hormonal imbalances, as discussed by Khalid et al. (2022).

Overall, the results demonstrate that the *A. nodosum* biostimulant mitigated sodicity effects and enhanced early growth parameters in both genotypes, with a more pronounced response observed in the tolerant genotype H. Kawandang. In SP80-1842, the biostimulant also enhanced shoot dry mass and the sodicity tolerance index under saline conditions, although the absolute values were lower. These findings confirm our first hypothesis that sugarcane genotypes exhibit variability in sodicity tolerance, as well as support the second hypothesis that seaweed-based biostimulant application can alleviate sodicity stress, particularly when paired with inherently tolerant germplasm. Therefore, the combined use of stress-tolerant genotypes and moderate doses of A. nodosum (around 5 mL L^{-1}) represents a promising strategy for improving sugarcane establishment in sodic soils.

Future studies integrating molecular and physiological approaches are warranted to elucidate the specific pathways modulated by A. nodosum under saline conditions. Additionally, field validation trials and investigations involving interactions with beneficial microorganisms may further strengthen sustainable management strategies for sugarcane cultivation in sodic environments.

4. Conclusions

This study revealed significant genotypic variability in sugarcane tolerance to sodic soil conditions. H. Kawandang showed the highest tolerance, followed by the energy cane hybrid Vertix 5, highlighting the potential of these materials for cultivation and as breeding resources for development of sugarcane cultivars for sodic environments. In the second experimental phase, the application of an *Ascophyllum nodosum*–based biostimulant improved early plant growth and increased the sodicity tolerance index in both the tolerant genotype (H. Kawandang) and the susceptible cultivar (SP80-1842), particularly at doses of approximately 5.0 mL L^{-1} under saline conditions.

Authors' Contribution

Watanabe, E.C.S.: Conceptualization, investigation, methodology, data curation, formal analysis, writing – original draft, and writing – review & editing. Silva, L.D.R.: Writing – original draft, writing – review & editing, and manuscript revision. Costa, N.: Investigation, field and greenhouse evaluations, data collection, writing – original draft, and writing – review & editing. Chales, A.S.: Investigation, field and greenhouse evaluations, data collection, writing – original draft, and writing – review & editing. Ferreira, A.L.P.: Writing – original draft, writing – review & editing, and manuscript revision. Pimentel, G.V.: Conceptualization, funding acquisition, methodology, formal analysis, supervision, project administration, writing – review & editing, and final approval of the manuscript.

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