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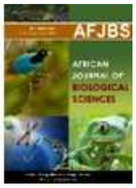

Research Paper

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Incidence of a biostimulant on the agronomic performance of corn under water stress

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SUMMARY

The decrease in rainfall leads to a drastic reduction in corn production. Thus, the use of an algae-based biostimulant was studied to improve corn growth and production under water stress conditions. To this end, four water regimes (25, 50, 75 and 100% of field capacity), all coupled with the application of biostimulant or not, were applied to plants of three corn varieties in greenhouse potting soil. From sowing to harvest, growth, phenological and yield parameters were evaluated. The results of the ANOVA test revealed that the decrease in the water regime significantly slows down plant growth, reduces their chlorophyll content, grain yield, and accelerates plant phenology. However, the application of the biostimulant significantly improved yield and its components from 1000 to 1700 kg/ha; from 1200 to 1900 kg/ha and from 1200 to 2300 kg/ha respectively in the yellow, purple and white varieties. In addition, the biostimulant significantly ($P < 0.001$) slowed down the effects of this decline through the maintenance of plant height, collar diameter, number of leaves, yield and accelerated phenology. In summary, the use of algae-based biostimulants could be an innovative solution to improve the resilience of maize crops to the challenges of increasing climate change, including drought.

Key words: *Zea mays*, biostimulant, water regime

INTRODUCTION

Maize (Zea mays L.) is a major food and industrial crop occupying a strategic position in numerous countries' agricultural systems and food security. Used as a foodstuff, livestock fodder and raw material in agro-industrial processes, maize plays a multifunctional role in many economies, both developed and developing. According to the FAO (2023), world maize production exceeded 1.2 billion tons, making it the world's leading cereal crop ahead of wheat and rice by 2022.

In Côte d'Ivoire, with production estimated at 1.2 million tons in 2021, maize ranks as the second most widely grown cereal after rice (MINADER, 2022). This plant is grown in almost all regions, notably the country center, northern and western, and is an essential foodstuff for both rural and urban populations. However, its domestic production remains below growing demand, forcing the country in resorting substantial imports to fulfil the shortfall. In addition, small-scale farmers, producing globally around 2 tons of maize per growing season (Boone *et al*., 2008) carry out most national production. Several constraints may explain this low yield. These include pests, diseases, nearly exhaustive use of low-yielding local varieties, weeds incidence (*Striga hermonthica*) and, above all, abiotic stresses due to climate change (Akanvou *et al*., 2006). Climate change is characterized by rising temperatures, reduced rainfall and their irregular cycles, and prolonged dry spells in Côte d'Ivoire. This reduces rainfed maize crop productivity, especially during sensitive stages like flowering and grain filling (Kouadio *et al.*, 2017). Water deficit appears to be one of the main factors limiting maize productivity, particularly in a context of increased climatic variability. It profoundly affects plant growth, photosynthesis, cell division and reproductive processes, thereby potentially leading to significant yield reductions (Farooq *et al*., 2009; Cakir, 2004).

Faced with this constraint, new agro-ecological approaches (creation of resistant varieties, use of irrigation) are being explored to improve crop resilience. Among these, algae-based biostimulants, rich in bioactive compounds (phytohormones, polysaccharides, amino acids, antioxidants), are attracting growing interest. Indeed, these substances regulate plant physiological and biochemical mechanisms (Aziz *et al*., 2003), promoting improved tolerance to biotic and abiotic stress (Norrie and Keathley, 2006; Eyras *et al*., 2008) and increased productivity, even under unfavorable conditions (Rouphael & Colla, 2020).

Moreover, biostimulants provide enhanced capillary activity for soil aeration and stimulate root system growth in plants (Moore, 2004). They also activate plants' natural defense systems by increasing bioactive molecule levels, notably antioxidants (Rayirath *et al*., 2009) and maintaining photosynthetic function under water stress (Goñi *et al*., 2018). Rathore's work (2009) showed that foliar spraying of algae extract-based biostimulants in soybeans promotes nutrient uptake and intensifies plant growth, resulting in higher yields. In maize and onions, their application led to an increase in chlorophyll (a and b) and carotenoid photosynthetic pigments (Abbas, 2020).

Despite these promising findings, recorded in several areas around the world, their actual effectiveness on crop production in Côte d'Ivoire, particularly under water-stressed conditions, remains largely non-existent. How these biostimulants interact with maize genotypes, water deficit levels and their effect on maize remains poorly understood. This problem raises pertinent issues for the present study, aiming at contributing to maize production improvement. Specifically, it aims at evaluating the impact of an algae-based biostimulant on maize growth and production under water-stressed conditions.

1-Materials and methods

1.1. Plant material and biostimulant

Pre-germinated grains of three maize varieties (Ferké White and Yellow, and Katiola Violet) were used as plant material. A mineral-enriched algal extract-based liquid solution (24.8 g/l boron; 0.23 g/l molybdenum; 43 g/l magnesia; 87.6 g/l sulfur oxide) served as biostimulant.

Figure 1. Pre-germinated grains of three mayze varieties: purple of Katiola, yellow and white of Ferké.

Figure 2. Bottle of BM Star algae-based biostimulant

1.2 Methods

1.2.1. Substrate production and determination of its water retention capacity

Substrate was prepared from sandy-clay soil and well-decomposed pig manure (in proportions of 2/3 and 1/3 V/V). After mixing by hand, the resulting substrate was sun-dried on a black polyethylene sheet until constant weight. A sample of this dry substrate, weighing around 6 kg, was removed with a spade and placed in a bucket. The whole bucket-substrate unit was weighed using a balance and its M_1 mass noted. This set was sprinkled with tap water until saturation, and then its new mass M_2 was noted after another weighing.

The difference in mass (M_2 - M_1), corresponding to the water quantity retained by the soil, served to calculate the water retention capacity (WRC) using the following formula:

$$\text{WRC} = \frac{M2-M1}{M1} \times 100 \quad (\%)$$

In practice, an 800 ml water volume was required for this retention capacity (WRC). Accordingly, this obtained WRC was considered as 100 wt. % water regime. Based on this, the other water regimes were determined: namely 800, 600, 400 and 200 ml of water, respectively corresponding to 100, 75, 50 and 25% water regime (**Figure 2**).

Figure 3. Transparent bottles containing 800, 600, 400, and 200 ml of water corresponding respectively to 100, 75, 50 and 25% of water regime (WR).

1.2.2- Mini greenhouse building and experimental set-up

In order to shelter the experiment and control the water regime (quantity of water supplied to plants), a mini greenhouse was built in a shed 3 m high, 12 m long and 12 m wide, i.e. a surface area of 144 m2. Its framework was made of Chinese bamboo trellis and its roof covered with a thin layer of mosquito netting topped with a polyethylene sheet. This sheeting was impermeable to rainwater but transparent to daylight. The mosquito netting absorbed heat induced by incident solar radiation to reduce the temperature under the mini-greenhouse. All perimeters were completely enclosed with mosquito netting to insulate the greenhouse against strong winds, insects and other pests. The greenhouse floor was covered with black plastic sheeting on which the seedling buckets were placed (**Figure 4**).

The previously manufactured substrate, tested for its water-retaining capacity (WRC), was split into buckets weighing 4 kg each. Buckets loaded in this way were laid out under the greenhouse in 4 rows (according to water regime) of 16 buckets each per variety. Then, 2 pre-germinated maize grains per bucket were sown at a 3 cm depth. Seedlings were abundantly watered with tap water. A week later, after germination, supernumerary plants were removed, leaving just one vigorous plant per bucket (**Figure 5**).

Figure 4. Experimental greenhouse

Figure 5. Layout of mayze young plant in buckets into the greenhouse

Starting from the second week until harvest, plants were watered with water volumes of 200, 400, 600 and 800 ml, corresponding respectively to 25, 50, 75 and 100 % water regime. For each water regime, a portion of plants was sprayed with the 15 ml of algal biostimulant (2 g/L) for each maize variety, while the other portion of plants received no biostimulant as a control. In all, 24 treatments were applied: four water regimes (25, 50, 75 and 100%) × three varieties (Ferké white, Katiola violet and Ferké yellow) × 2 treatments (biostimulant or not). Various maintenance operations (weeding and phytosanitary treatment) were applied as required.

1.2.3- Harvest and post-harvest treatment

When cobs reached maturity, characterized by a change in spathe color from green to brown, they were manually harvested by separating them from the mother plants. The harvested cobs were de-shelled for ginning and measurement (**Figure 6**).

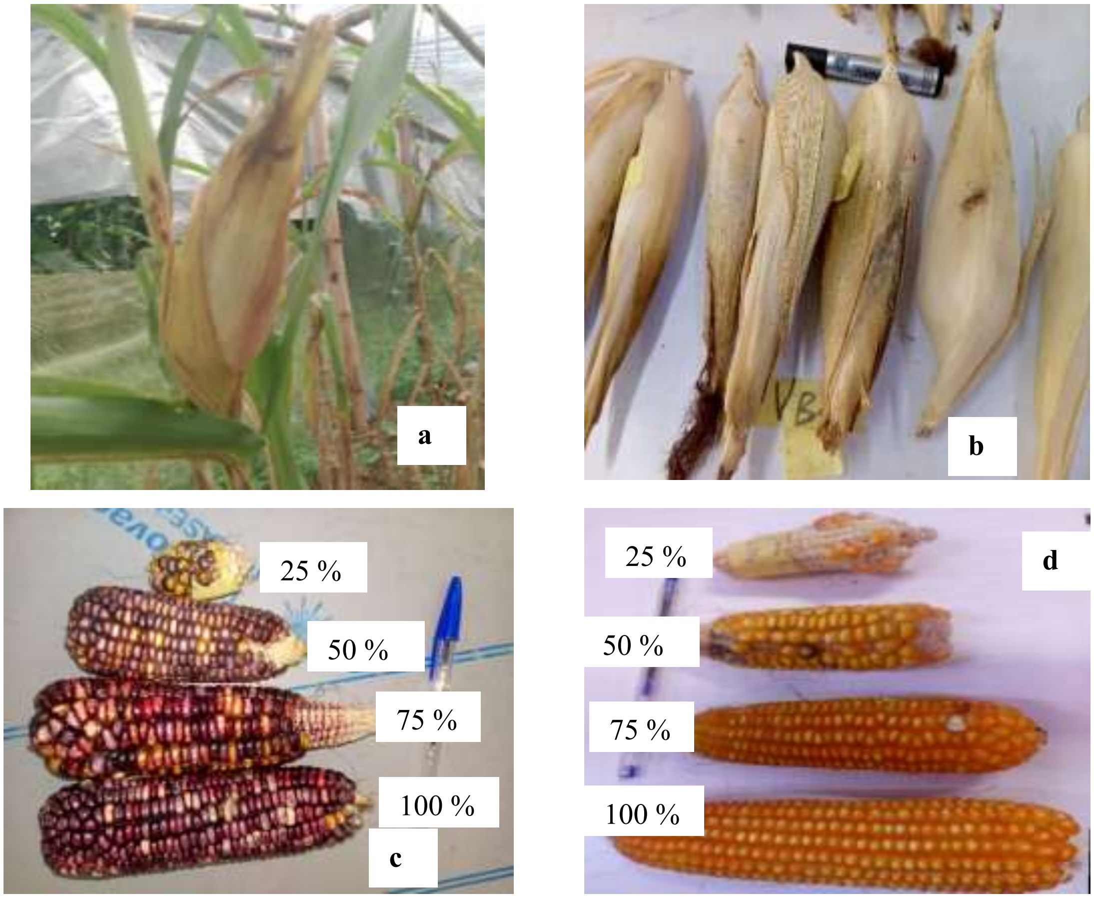

Figure 6. Maturation (a), harvest (b), and post-harvest of maize purple (c) and yellow (d) varieties cobs. Percentages correspond to water regimes.

1.2.4. Maize agronomic parameter measurements

During this study, five growth parameters (number of leaves, plant height and stem collar diameter), one physiological parameter (total chlorophyll content), three phenological parameters (stamen appearance dates, cob emergence and maturation dates) and seven yield parameters [cob length and weight, number of kernels carried/ cob, dimensions (width, thickness and thickness) and kernel weight] were assessed. Cobb numbers were obtained by hand-counting; plant height was measured with a tape measure, and crown diameter with a caliper. Grain number per cob was obtained by counting, and 100-grain weight was measured using an electronic balance. Total chlorophyll content was measured using a chlorophyll meter.

1.2.5. Data statistical processing

All data collected in this study were statistically analyzed using SAS statistical software (SAS, 2004). Analysis of variance with three classification criteria (ANOVA 3) was performed to test individual then combined effect of the studied factors (maize variety, watering rate and biostimulant). When the null hypothesis was rejected for each parameter, multiple comparisons using the Least Significant Difference (LSD) were carried out test to separate the means (Dagnélie, 1998). All the tests were performed at α = 0.05 significance level.

2. RESULTS AND DISCUSSION

2.1. Results

2.1.1. Effect of biostimulant on maize plant growth and phenology under water stress

Growth parameters (number of leaves and roots, crown diameter and plant height) and phenological parameters (male and female flowering and ripening dates) varied significantly with water regime (from 100% to 25%), biostimulant application and maize variety (**Tables 1 and 2**). For all the three maize varieties (yellow, violet and white), despite optimal water conditions (100% w.r.), biostimulant application boosted growth parameters and accelerated plant phenology. For yellow varieties, for example, biostimulant application at 100% w.r. led to an increase in plant height (from 144.95 to 148.20 cm), collar diameter (from 10.45 to 15.32 mm) and leaf number (from 8.91 to 9.30 leaves/plant). This application also favored root emission for yellow varieties (from 25 to 32 roots), white (from 27 to 33 roots) and especially violet (from 26 to 37 roots). On the other hand, it accelerated male flowering (from 54.33 to 52 days ago), female flowering (from 54.33 to 53.00 days ago) and ripening (from 93.16 to 71.66 days ago).

Lowering water regime (from 100% to 25% RH) reduced growth parameter values across these varieties. For example, in purple, this drop in rh led to a reduction in plant height (from 139.25 to 120.91 cm), collar diameter (from 10.45 to 6.72 mm), number of leaves carried (from 7.63 to 5.06 leaves/plant) and root -bearing (**Figure 7**) (from 26 to 11). Moreover, despite the most severe water regime (25% RH), biostimulant application maintained plant height (137.43 vs. 130.71 cm), crown diameter (11.63 vs. 6.72 cm), and reduced leaf drop (6.90 vs. 5.06 leaves/plant). Biostimulant application also enabled root numbers to be maintained at 37 versus 26, 32 versus 23, 27 versus 21 and 26 versus 11 respectively for 100-75, 50 and 25% water regimes.

However, this drop in HR led to an acceleration of male flowering (from 58.25 to 54.33 days ago) in control plants and from 54.66 to 52 days ago in treated plants. Similarly, cobs onset was accelerated (from 58.25 to 54.33 JAS in raw plants and from 66.16 to 53 JAS in treated plants), as was cob ripening (from 84.5 to 78.5 JAS in raw plants and from 81.16 to 74 JAS). What's more, biostimulant application reduced the effects of each water regime.

In sum, despite optimal water conditions (100% RH), biostimulant application favored growth parameters and accelerated plant phenology. The drop in water regime reduced plant radial growth, height growth and leaf emission, and accelerated growth phenology in plants of all three maize varieties. Nevertheless, applying the biostimulant significantly reduced this drop. The yellow and white varieties seemed to maintain higher growth than the purple variety, which suffered the greatest leaf loss under water stress. Therefore, the algae-based biostimulant promotes root growth in corn whatever the water regime. In the event of water stress, it slows down the effect on root emission.

Table 1. Biostimulant effect on plant growth under water stress in maize

Varieties	Water regime	Plant growth parameters					
		Plant height (cm)		Stem collar diameter (mm)		Leaves per plant	
		Biostimulant	Control	Biostimulant	Control	Biostimulant	Control
Ferké yellow	100 %	148.20 ± 4.20 ^{ab}	144.95 ±3.19^{abcdef}	15.32 ± 0.73 ^{abc}	10.45 ± 0.66 ^{ghi}	9.30 ± 0.36 ^{ab}	8.91 ± 0.31^{abcdef}
	75 %	146.76 ± 3.83 ^{abcd}	142.30 ± 3.02^{bcdef}	13.03 ± 0.60 ^{cd}	8.83 ± 0.56 ^{hij}	8.90 ± 0.35 ^{abcd}	8.41 ± 0.34 ^{bcdef}
	50 %	144.25 ± 3.20^{abcde}	140.48 ± 3.11^{bcdef}	16.68 ± 2.95 ^{ab}	8.14 ± 0.64 ^{ij}	8.41 ± 0.28 ^{abcdef}	8.20 ± 0.34 ^{bcdef}
	25 %	137.43 ± 2.90 ^{gh}	130.71 ± 2.91^{dcefg}	10.74 ± 0.55 ^{gh}	6.72 ± 0.67 ^{j}	8.51 ± 0.26 ^{bcdef}	8.03 ± 0.36 ^{defgh}
Purple Katiola	100 %	145.99 ± 4.26^{abcde}	139.25± 3.36^{bcdefg}	15.38 ± 0.74 ^{abc}	10.45 ± 0.66 ^{ghi}	8.86 ± 0.44 ^{bcd}	7.63 ± 0.44 ^{bcdef}
	75 %	136.74 ± 3.66 ^{fgh}	130.93 ± 2.88 ^{gh}	13.03 ± 0.60 ^{bcd}	8.83 ± 0.53 ^{hij}	7.56 ± 0.66 ^{efg}	6.48 ± 0.34 ^{cdefg}
	50 %	136.28 ± 3.27 ^{fgh}	129.68 ± 2.89 ^{hi}	16.12 ± 2.98 ^{abc}	8.14 ± 0.64 ^{ij}	8.40 ± 0.86 ^{bcde}	6.13 ± 0.35 ^{cdefg}
	25 %	130.43 ± 2.90 ^{gh}	120.91 ± 2.44 ^{gh}	11.63 ± 0.40 ^{hij}	6.72 ± 0.64 ^{j}	6.90 ± 0.33 ^{ghi}	5.06 ± 0.42 ^{j}
Ferké white	100 %	152.31 ± 4.23 ^{a}	142.66 ± 3.42^{bcdef}	16.02 ± 0.62 ^{abc}	10.23 ± 0.59 ^{ghi}	10.01 ± 0.40 ^{a}	8.98 ± 0.32 ^{efg}
	75 %	147.41 ± 3.88 ^{abc}	139.00± 3.14^{abcde}	13.53 ± 0.56 ^{cd}	8.92 ± 0.52 ^{hij}	8.91 ± 0.35 ^{abc}	8.10 ± 0.29 ^{hi}
	50 %	144.53 ± 3.26^{abcdef}	139.05 ± 2.78^{cdefg}	17.37 ± 0.51^{a}	8.50 ± 0.58 ^{hij}	9.20 ± 0.30 ^{abcdef}	8.15 ± 0.31^{i}
	25 %	137.65 ± 2.50 ^{fghi}	129.15 ± 2.07 ^{fghi}	11.16 ± 0.48 ^{hij}	6.63 ± 0.63 ^{j}	8.48 ± 0.27 ^{efgh}	7.33±0.33 ^{ij}
Statistics	*F*	3.73		1.94		2.90	
	P	< 0.001		0.004		< 0.001	

, F-statistics and P: probability associated with the test. For each parameter, values with the same superscript letters are statistically equal ($P \geq 0.05$).

Table 2. Influence of biostimulant on plant phenology in water-stressed maize.

Varieties	Water regime	Plant phenological parameters					
		Stamen appearance date (DAS)		Cobs onset date (DAS)		Cobs maturation date (DAS)	
		Biostimulant	Control	Biostimulant	Control	Biostimulant	Control
Ferké yellow	100 %	50.16 ± 0.63 ^{def}	53.16 ± 0.42 ^{abcd}	59.08 ± 0.72 ^{hi}	60.91 ± 0.80 ^{gh}	71.66 ± 1.08 ^{a}	93.16 ± 1.26 ^{hi}
	75 %	52.08 ± 0.71 ^{cde}	53.50 ± 0.69 ^{abcd}	61.25 ± 1.09 ^{fgh}	64.75 ± 0.41 ^{gh}	73.25 ± 0.80 ^{ab}	88.33 ± 2.06 ^{gh}
	50 %	52.75 ± 0.88 ^{bcd}	54.50 ± 0.19 ^{abcd}	60.16 ± 1.11 ^{hi}	64.41 ± 0.43 ^{bcde}	73.25 ± 1.20 ^{ab}	87.91 ± 1.66 ^{gh}
	25 %	54.83 ± 0.45 ^{abcd}	57.08 ± 0.76 ^{abc}	63.25 ± 0.90 ^{cdef}	65.50 ± 0.59 ^{ab}	73.58 ±0.96 ^{abc}	95.00 ± 0.70 ^{i}
Purple Katiola	100 %	52.00 ± 0.81 ^{cde}	54.33 ± 1.54 ^{abcd}	53.00 ± 0.81 **i**	54.33 ± 1.54 ^{cdef}	74.00 ± 1.38 ^{abc}	78.50 ± 1.14 ^{bcde}
	75 %	56.33 ± 0.65 ^{abc}	57.58 ± 1.33 ^{ab}	57.33 ± 0.65 ^{efg}	57.58 ± 1.33 ^{abcd}	76.58 ± 1.02 ^{abcd}	84.16 ± 1.79 ^{efg}
	50 %	55.16 ± 0.57 ^{abcd}	54.50 ± 0.19 ^{abcd}	56.16 ± 0.57 ^{defg}	64.41 ± 0.43 ^{bcde}	76.50 ± 1.43 ^{abcd}	79.25 ± 7.3 ^{cdef}
	25 %	54.66 ± 1.07 ^{abcd}	58.25 ± 0.64 ^{a}	66.16 ± 0.24 ^{ab}	58.25 ± 0.64 ^{ab}	81.16 ± 1.48 ^{def}	84.5 ± 1.43 ^{fg}
Ferké white	100 %	43.33 ± 2.79 ^{gh}	41.75 ± 2.76 ^{h}	62.83 ± 0.61 ^{defg}	61.08 ± 1.22 ^{fgh}	77.33 ± 1.93 ^{abcd}	79.16 ± 2.43 ^{cdef}
	75 %	43.91 ± 3.18 ^{gh}	45.58 ± 2.85 ^{fgh}	63.16 ± 0.75 ^{cdef}	65.33 ± 0.74 ^{abc}	74.16 ±1.40 ^{abc}	87.33 ± 1.81 ^{gh}
	50 %	42.41 ± 3.21 ^{gh}	42.91 ± 2.73 ^{gh}	64.50 ± 0.91 ^{bcde}	63.00 ± 1.14 ^{defg}	75.33 ± 1.11 ^{abcd}	87.66 ± 1.62 ^{gh}
	25 %	44.41 ± 3.11 ^{gh}	47.25 ± 2.85 ^{efg}	64.66 ± 0.91 ^{abcd}	66.75 ± 0.50 ^{a}	78.66 ± 1.83 ^{bcdef}	88.5 ± 1.43 ^{gh}
Statistics	***F***	**3.24**		**5.71**		**2.33**	
	P	**< 0.001**		**< 0.001**		**0.03**	

WR: water regime, **DAS**: days after sowing, F-statistics and P: probability associated with the test. For each parameter, values with the same superscript letters are statistically equal ($P \geq 0.05$).

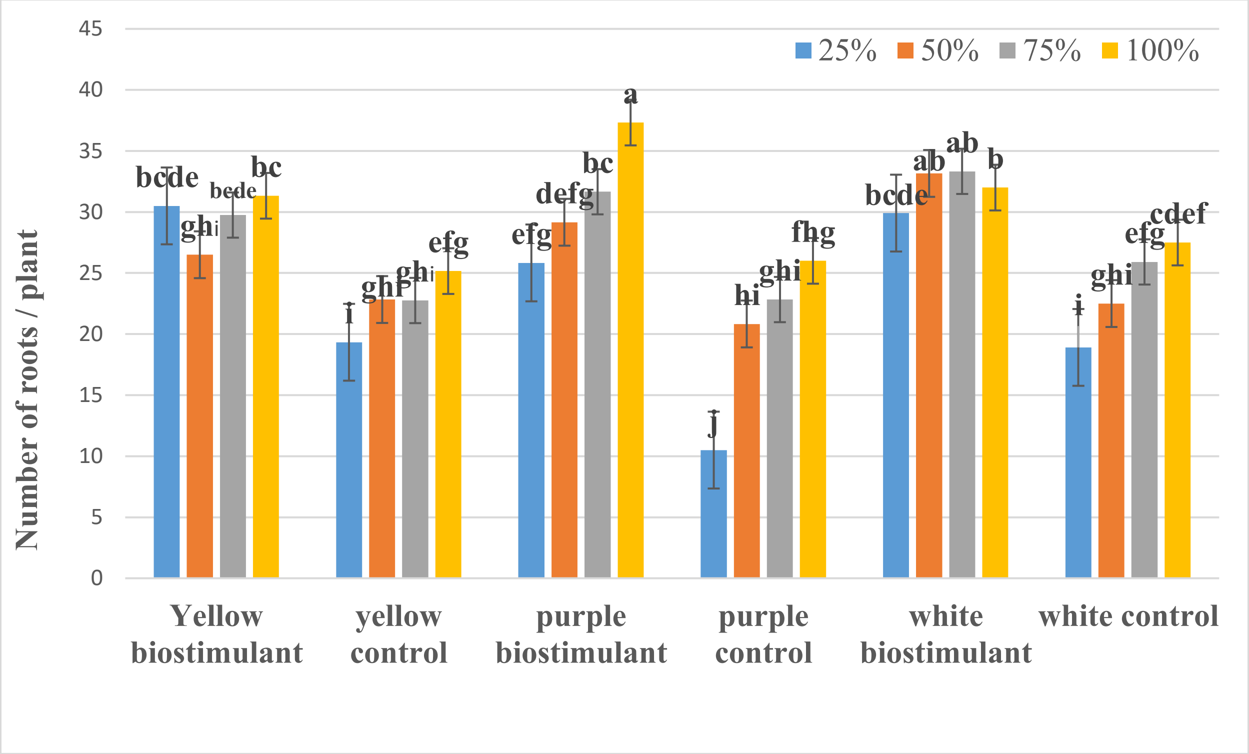

Figure 7. Histogram showing biostimulant effect on root number evolution under various water regimes in maize.

2.1.2. Effect of biostimulant on total chlorophyll content

Corn leaves grown under various water stress conditions showed significant changes in total chlorophyll content, depending on variety and availability of algal biostimulant (**Figure 8**).

Decline in water regime (from 100% to 25%) led to a reduction of leaf total chlorophyll content. For example, in the FMB variety, total chlorophyll levels fell from 29 to 17 mg/g in biostimulated plants, compared with 20 to 16 mg/g in controls. Applying biostimulants attenuated this drop in total chlorophyll content, induced by the reduced water regime.

Thus, applying biostimulant increases total chlorophyll content in maize plants grown under normal moisture conditions, and reduces its decline under water stress. Moreover, under severe stress (25%), chlorophyll-rich yellow and FMB varieties proved less sensitive than the purple variety.

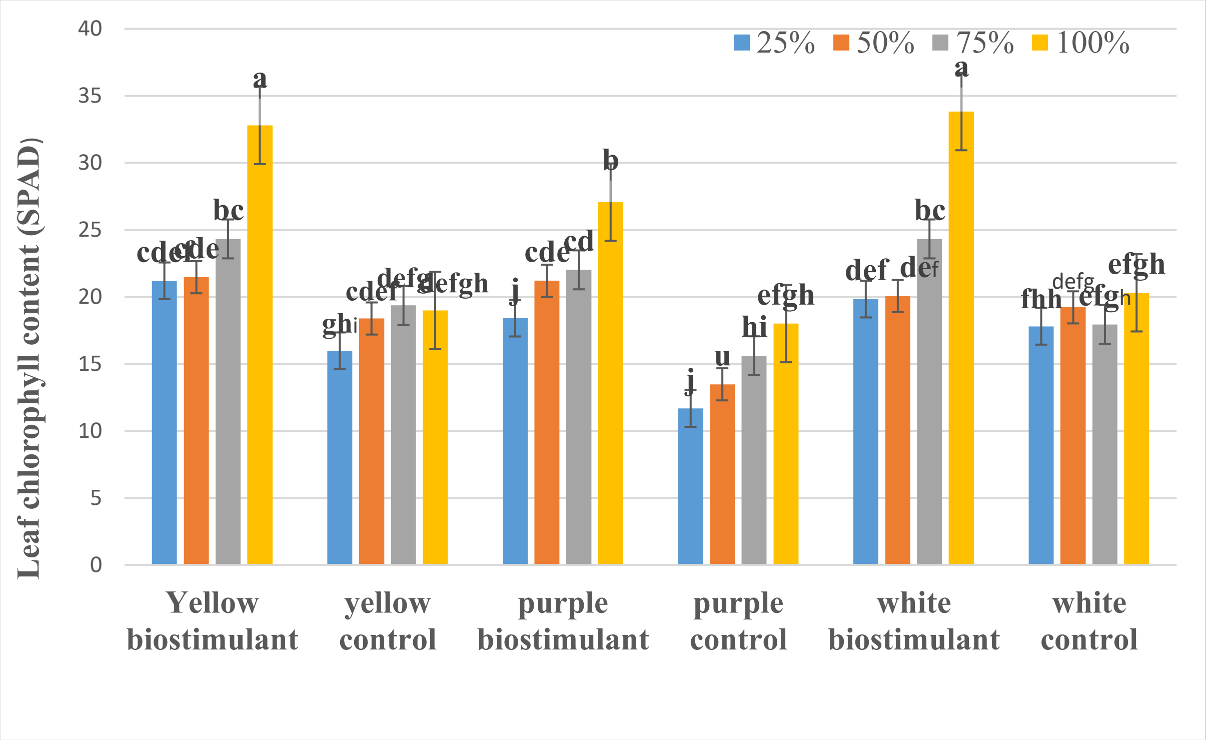

Figure 8. Biostimulant effect on leaf total chlorophyll content variation depending on water regime in maize varieties.

2.1.3. Effect of biostimulant on yield and yield parameters in maize facing water stress

Effect on yield parameters

Yield parameters, relating to cobs (number and weight) grown per plant and their grains' sizes (length, width and thickness), vary significantly (P < 0.001) over four water regimes, and depending on biostimulant in the three maize varieties (**Tables 3 and 4**).

Compared to controls without biostimulant, biostimulant application led to an increase in both cob number per plant (from 1.00 to 1.66), and their weight (from 27, 65 to 43.65 g), grain size (8.92 to 12.84 mm length, 10.28 to 12.20 mm width and 4.75 to 6.67 mm thickness) and their total weight (21.10 to 35.95 g). Similarly, weighing 100 grains increased (12.55 to 30.20 g). Similar results were obtained for both other varieties (white and violet). Moreover, in every variety whether treated or not with the biostimulant, drop in water regime (from 100% to 25%) led to lower yields in terms of cobs (number and weight), grain size (length, width and thickness) and weight (total and per 100). For example, in violet control, these drops in water regime led to a reduction in cob production (from 1 to 0.66 cobs/plant) and their weight (from 29.55 to 7.03 g), as well as grain size (from 8.67 to 5.36 mm in length, from 10 to 6.72 mm in width and from 4.5 to 1.19 mm), weight (from 23.56 to 5.77) and 100-grain weight (from 20.15 to 4.55 g).

Overall, the decrease in water regime led to lower grain yields in all three maize varieties. Biostimulant application significantly improved yields and yield parameters in all three maize varieties under optimum water conditions, but also limited the yield-parameter decline due to lower water regimes, especially under severe stress.

Table 3. Impact of biostimulant on cob production and their grain size follwing water regime in mayze

Varieties	WR	Yield component							
		Cobs parameters				Grains parameters			
		Number/ plant		Weight (g)		Thickness (mm)		Width (mm)	
		Biostimulant	Control	Biostimulant	Control	Biostimulant	control	Biostimulant	control
Ferké yellow	100%	1.58 ± 0.14 ^{a}	1.00 ± 0.00 ^{cdef}	43.65 ± 1.97 ^{ab}	27.65 ± 1.46 ^{ef}	6.47 ± 0.33 ^{ab}	5.18 ± 0.35 ^{cde}	11.74 ± 0.30 ^{a}	10.44 ± 0.26 ^{bc}
	75%	1.41 ± 0.14 ^{ab}	1.00 ± 0.00 ^{cdef}	32.40 ± 1.30^{cde}	18.80 ± 1.51 ^{gh}	5.51 ± 0.32 ^{bcd}	4.17 ± 0.23 ^{fghi}	11.04 ± 0.32 ^{abc}	9.70 ± 0.23 ^{efg}
	50%	1.08 ± 0.08 ^{cde}	0.91 ± 0.08^{defg}	27.62 ± 0.78 ef	14.60 ± 2.33 ^{hi}	4.68 ± 0.09 ^{defg}	3.20 ± 0.34 ^{jk}	10.18 ± 0.10^{cdef}	8.63 ± 0.33 ^{hij}
	25%	1.16 ± 0.11 ^{bcd}	0.50 ± 0.15 ^{h}	20.32 ± 2.37 ^{gh}	6.95 ± 2.43 ^{j}	2.86 ± 0.23 ^{jk}	1.65 ± 0.20 ^{ln}	8.40 ± 0.24 ^{ij}	7.07 ± 0.20 ^{kl}
Purple Katiola	100%	1.58 ± 0.14 ^{a}	1.00 ± 0.00 ^{cdef}	44.60 ± 1.79 ^{a}	29.55 ± 1.26^{def}	5.96 ± 0.38 ^{abc}	4.50 ± 0.37^{efgh}	11.49 ± 0.38 ^{ab}	10.03 ± 0.37 ^{de}
	75%	1.25 ± 0.13 ^{bc}	0.91 ± 0.08^{defg}	34.40 ± 2.67 ^{cd}	24.55 ± 1.45 ^{fg}	5.04 ± 0.22 ^{cdef}	4.06 ± 0.30 ^{fghi}	10.42 ± 0.17^{bcde}	9.31 ± 0.20 ^{efg}
	50%	1.16 ± 0.11 bcd	0.91 ± 0.08^{defg}	16.55 ± 0.83 ^{h}	15.45 ± 0.60 ^{hi}	3.99 ± 0.18 ^{ghi}	2.90 ± 0.15 ^{jk}	9.46 ± 0.19 ^{fgh}	8.34 ± 0.13 ^{ij}
	25%	1.00 ± 0.00 ^{cdef}	0.66 ± 0.14 ^{gh}	14.90 ± 0.77 ^{hi}	7.03 ± 4.12 ^{j}	3.47 ± 0.95 ^{ijk}	1.19 ± 0.24 ^{n}	9.00 ± 0.95 ^{hij}	6.72 ± 0.24 ^{l}
Ferké withe	100%	1.66 ± 0.14 ^{a}	1.00 ± 0.00 ^{cdef}	49.32 ± 4.42 ^{a}	29.77 ± 0.52^{def}	6.67 ± 0.52 ^{a}	4.75 ± 0.52^{defg}	12.20 ± 0.52 ^{a}	10.28 ± 0.52 ^{ec}
	75%	1.58 ± 0.14 ^{a}	1.00 ± 0.00 ^{cdef}	37.80 ± 4.73 ^{bc}	27.87 ± 4.46^{def}	4.92 ± 0.37 ^{defg}	2.69 ± 0.33 ^{hij}	10.45 ± 0.37^{cdef}	9.22 ± 0.33 ^{ghi}
	50%	1.25 ± 0.13 ^{bc}	1.00 ± 0.00 ^{cdef}	18.62 ± 1.36 ^{gh}	16.65 ± 0.85 ^{h}	4.07 ± 0.26 ^{fghi}	2.53 ± 0.24 ^{kl}	9.60 ± 0.26 ^{efgh}	8.06 ± 0.24 ^{jk}
	25%	1.08 ± 0.08 ^{cde}	0.83 ± 0.11 ^{efg}	14.52 ± 1.48 hi	8.97 ± 3.06 ^{ij}	2.93 ± 0.21 ^{ijk}	1.11 ± 0.17 ^{n}	8.46 ± 0.21 ^{ij}	6.64 ± 0.17 ^{l}
Statistics	***F***	**42.55**		**2.03**		**3.52**		**3.29**	
	P	**< 0.001**		**0.01**		**< 0.001**		**< 0.001**	

F-statistics and P: probability associated with the test. For each parameter, values with the same superscript letters are statistically equal (P ≥ 0.05).

Table 4. Biostimulant effect on yield parameters under water stress in four maize varieties

Varieties	WR	Yield components					
		Grain length (mm)		Grain weight / cob (g)		100-grain weight (g)	
		Biostimulant	Control	Biostimulant	Control	Biostimulant	Control
Ferké yellow	100 %	10.38 ± 0.30 ^{ab}	9.08 ± 0.26 ^{cd}	35.95 ± 2.13 ^{cb}	21.10 ± 1.51 ^{fgh}	30.20 ± 2.33 ^{bc}	12.55 ± 3.44 ^{gh}
	75 %	9.68 ± 0.32 ^{bc}	8.34 ± 0.23 ^{cde}	22.66 ± 1.41 ^{f}	14.87 ± 0.87 ^{ij}	18.14 ± 1.23 ^{f}	11.72 ± 0.53 ^{ghi}
	50 %	8.82 ± 0.10 ^{cdef}	7.27 ± 0.33 ^{ijk}	21.37 ± 0.82 ^{fg}	11.51 ± 1.37 ^{jkl}	16.82 ± 0.65 ^{fg}	9.15 ± 0.83 ^{hij}
	25 %	7.70 ± 0.35 ^{jk}	5.71 ± 0.20 ^{l}	15.25 ± 1.82 ^{hij}	5.80 ± 2.14 ^{l}	12.06 ± 1.41 ^{gh}	4.77 ± 1.68 ^{j}
Purple katiola	100 %	10.13 ± 0.38 ^{ab}	8.67 ± 0.37^{defg}	39.75 ± 2.55 ^{ab}	23.56 ± 1.31 ^{f}	34.70 ± 2.33 ^{ab}	20.15 ± 1.28 ^{f}
	75 %	9.06 ± 0.17 ^{cde}	7.95 ± 0.20 ^{fghi}	29.57 ± 2.47 ^{de}	19.57 ± 0.91^{fgh}i	25.42 ± 2.61^{cde}	17.02 ± 0.55 ^{fg}
	50 %	8.10 ± 0.19 ^{efgh}	6.98 ± 0.13 ^{jk}	13.79 ± 1.00 **ij**	12.79 ± 0.42 ^{jk}	11.25 ± 1.12 ^{hi}	10.47 ± 0.77 ^{hi}
	25 %	7.64 ± 0.95 ^{jk}	5.36 ± 0.24 ^{l}	11.05 ± 0.91 ^{ijk}	5.77 ± 3.38 ^{l}	8.87 ± 0.54 ^{hij}	4.55 ± 2.63 ^{j}
Ferké withe	100 %	12.84 ± 0.52 ^{a}	8.92 ± 0.52^{cdef}	44.01 ± 4.88 ^{a}	25.07 ± 0.53 ^{ef}	37.71 ± 3.53 ^{a}	22.15 ± 0.64 ^{def}
	75 %	9.09 ± 0.37 ^{cd}	7.86 ± 0.33 ^{ghij}	31.00 ± 4.07 ^{cd}	21.65 ± 2.44 ^{f}	27.00 ± 4.02 ^{cd}	19.32 ± 2.02 ^{f}
	50 %	8.24 ± 0.26 ^{defg}	6.70 ± 0.24 ^{k}	15.52 ± 0.89 ^{ghij}	14.07 ± 1.02 ^{ij}	12.53 ± 1.12 ^{gh}	11.95 ± 1.13 ^{gh}
	25 %	7.10 ± 0.21^{jk}	5.28 ± 0.17 ^{l}	10.80 ± 1.12 j^{kl}	7.22 ± 2.46 ^{kl}	8.48 ± 0.49 ^{hij}	6.31 ± 2.16 ^{ij}
Statistics	***F***	**3.29**		**2.27**		**4.69**	
	P	**< 0.001**		**0.004**		**< 0.001**	

F-statistics and P: probability associated with the test. For each parameter, values with the same superscript letters are statistically equal (P ≥ 0.05)

Effect on grain yield

Yield component values varied significantly with water availability, biostimulant, and maize varieties studied (**Figure 9**). At full field capacity (100%), biostimulant application boosted yield from 1,000 to 1,700 kg/ha for yellow variety, from 1,200 to 1,900 kg/ha for purple variety, and practically doubled it from 1,200 to 2,300 kg/ha for white variety. Globally, reduced water regime (from 100 to 25%) led to a decrease in maize grain yield from 1100 to 350 Kg/ha for yellow varieties, from 1200 to 350 Kg/ha for violet and from 1300 to 400 Kg/ha for white. Under the harshest water regime (25%), the yellow variety proved less sensitive than violet and white. Moreover, for each water regime, yields from biostimulant-treated plants were higher than control plants in all three varieties. For example, in white, applying the biostimulant maintained yields at 2300 against 1200 Kg/ha, 1500 against 1100 Kg/ha, 700 against 600 Kg/ha and 500 against 350 Kg/ha for 100, 75, 50 and 25 % water regime respectively. This indicates that the biostimulant reduced yield losses in all varieties.

Decreasing water levels (100% to 25% RH) resulted in lower yields across all three varieties. However, biostimulant application improved maize yield under severe stress conditions (50% and 25% RH).

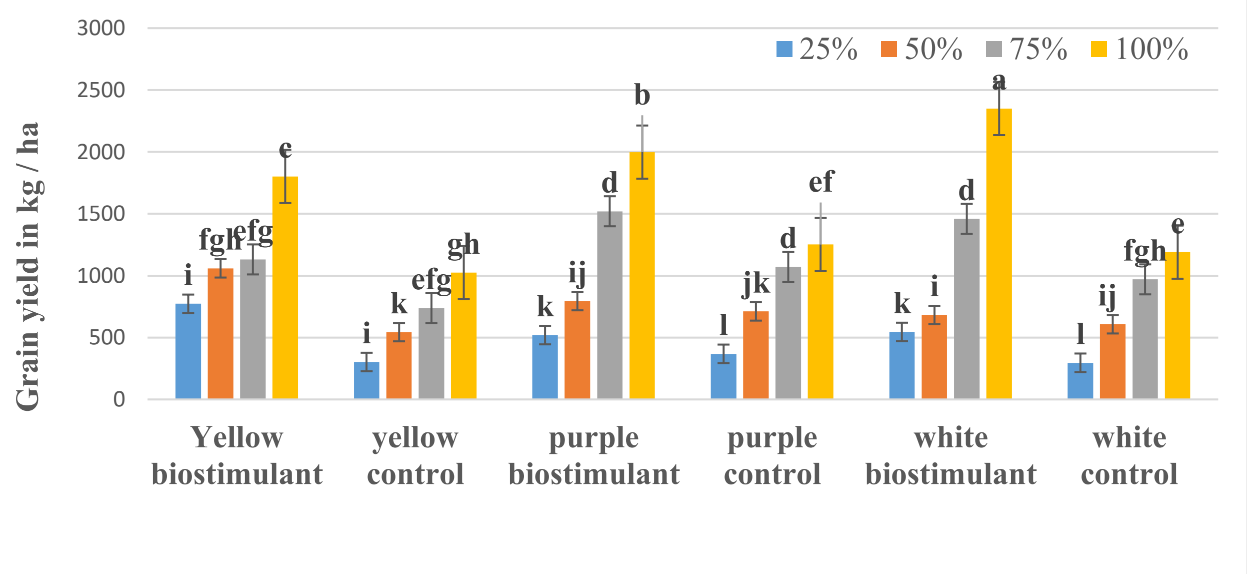

Figure 9. Effect of biostimulant on yield of three maize varieties under water stress.

2.2. Discussion

Maize is a grain that is highly sensitive to water deficit, significantly affecting its production (Daryanto *et al*., 2016). In a bid to improve its production, biostimulant based on seaweed extracts was evaluated for its ability to reduce the negative effects of water deficit. Aiming at improving its production, biostimulant based on seaweed extracts was tested to mitigate the adverse effects of water deficit through physiological, growth, phenology and yield parameters in three maize varieties (yellow and white from Ferké and purple from Katiola). This study shows that, as well as mitigating growth decline caused by reduced water availability (from 100% to 25%), this biostimulant significantly improved agronomic parameters under optimal moisture conditions (100% water availability) in the three varieties of maize tested.

Applied under optimal moisture conditions (100% water regime), the algae-based biostimulant significantly improved vegetative growth parameters among the three maize varieties tested, including root development, plant height, collar diameter, and number of leaves. It also accelerated phenology and increased corn plant yield. This improvement in roots could be why biostimulants help them grow, so they can recover well and then help the plant grow. Faessel *et al*. (2014) previously reported that biostimulants activate root growth and plant development. According to Moore (2004), increased root development allows plants to explore deeper into the soil in search of water and nutrients, resulting in better absorption. It is possible that increased root development improves plant growth and development. These results could also be attributed to how rich the biostimulant is, based on algae extracts and natural growth hormones like cytokinins, auxins, and gibberellins, and these help with cell meresis and auxesis, leading to plant tissue differentiation (Calvo *et al*., 2014). Plant growth and development improvements in both maize varieties studied would naturally induce their best performance through large cobs, comprising lots of big and heavy grains leading to high yields. Another possible explanation for this performance is the algae extracts' ability to stimulate photosynthetic pigment biosynthesis and protect chloroplast membranes with natural antioxidants. According to Abbas (2020), biostimulants help maintain photosynthetic activity, essential to plant metabolism and therefore to plant growth and reproduction.

The water regime also affected the crops' agronomic performance. In fact, the decrease in water availability (from 100 to 25%) reduced radial and height growth, leaf emission, and photosynthetic activity, and delayed phenology and production in the three corn varieties studied.

This performance decline resulted in small plants carrying fewer and fewer leaves with low photosynthetic activity (total chlorophyll content) and a drop in production due to a reduction in number of cobs formed carrying very small and light grains. The effect of reduced water availability, caused by the numerous and recurring droughts currently occurring, is well documented. Zhang *et al.* (2022) noted that rainfall significantly affects maize production. According to them, reduced rainfall intensifies yield declines in this crop. In addition, Ogisi & Begho (2023) reported that climate change, especially lower rainfall, leads to a drastic reduction in agricultural production, requiring farmers to adopt new strategies.

This is why the effect of algae-based biostimulants on the agronomic performance of the three corn varieties was studied. The results show that water stress, particularly severe drought (25% RH), leads to significant reductions in plant height, collar diameter, number of leaves, and root development, especially in the control plants (untreated). However, treated plants showed an increase in the number of cobs per plant, as well as in the length, width, thickness, and weight of the kernels, even under severe water stress conditions at 25% RH. Therefore, biostimulant application significantly mitigates this drop. This ability could be due to improved photosynthesis, reduced water loss, and improved plant cell resistance to stress. It also highlights biostimulants' dampening effect, curbing drought-related yield declines. In fact, according to Calvo *et al*. (2014) and Rouphael & Colla (2020), biostimulants improve crop tolerance to abiotic stress while maintaining productivity. In addition, the positive effects of algae are generally attributed to their polysaccharide content, which promotes good soil structure. Oniang'o *et al* (2021) have also obtained better yield and good quality of marketable rose stems by spraying different biostimulants In addition, biostimulant-treated plants reach stamen and pistil maturity, as well as cob maturity, faster than controls. This phenological precocity can be beneficial in situations of water stress, as they allow the plant to complete its cycle before the stress reaches critical levels. Avoidance, therefore, is an adaptation strategy. Rathore (2009) also reported precocious phenological stages in soybeans after treatment with algae-based biostimulants. All these results suggest a protective role of the biostimulant against water stress effects. Indeed, algal extracts contain natural osmoregulators (mannitol, betaine, polysaccharides) which improve cell water retention, maintaining tissue turgidity and reducing oxidative damage (Rayirath *et al*., 2009).

As a result, the algae-based biostimulant appears to have strengthened mayze plants' physiological resilience to water deficit (Rouphael & Colla, 2020). It is also possible that these improvements might be linked to better nutrition (through more efficient root absorption) and increased photosynthesis (Norrie & Keathley, 2006; Eyras *et al*., 2008). According to Faessel *et al*. (2014), biostimulants activate root growth, which improves soil exploration for water and nutrients, leading to healthy plant development.

However, it depends on the maize varieties tested how the biostimulant can reduce water stress. The yellow and white varieties seem to stay growing better than the purple variety, which suffered the most leaf loss and lowest cob production due to water stress. This difference in variety tolerance to water stress is most likely related to their genetic characteristics. So, studying maize diversity, Tripathi *et al*. (2020) found some local varieties tolerant to water stress and therefore resilient to climate change. Accordingly, certain corn varieties possess more effective stress tolerance mechanisms, notably through better water management and an increased capacity to maintain photosynthetic activity even under water stress. Violette may be less effective at managing water resources, resulting in greater leaf loss. Moreover, several studies and experiments have clearly shown that, despite its good organoleptic qualities (Akaffou *et al*., 2018), Katiola's purple variety is very sensitive to several environmental factors such as weed growth (Yao *et al*., 2021), reduced rainfall, and pests.

Conclusion

This study highlighted the importance of decreased rainfall through changes in water regime (from 100 to 25% of field capacity) on growth, phenological, physiological, and yield parameters of three maize varieties (yellow, white of Ferké, and purple of Katiola). So, water reduction (from 100 to 25%) leads to lower growth through decreased plant height and diameter at the collar, fewer leaves, and lower yield. Therefore, water regime reduction (from 100 to 25%) leads to decreased growth through reduced plant height and collar diameter, and a decrease in the number of leaves bearing. Physiologically, this manifests in lower chlorophyll content, forcing plants to adapt by reducing their phenological life cycle, size, number of cobs formed, and grain yield. This adaptation strategy is known as avoidance.

Biostimulant application improved crop performance in all three maize varieties, not only under optimal water conditions, but also especially under severe water stress (25%). It appears to be an effective strategy for mitigating the adverse effects of water stress on maize plant development, particular by strengthening their ability to maintain high chlorophyll levels in order to continue photosynthesis under water stress. This helps to reduce grain yield decline. However, this biostimulant's ability to reduce water stress in plants seems to be really linked to the variety. Therefore, the yellow variety was more sensitive (with 0.5 ears/plant); the purple variety was moderately sensitive (0.66 ears/plant); and the white variety was less sensitive (0.83 ears/plant).

To sum up, using algae-based biostimulants could be an innovative way to improve the maize crop's resilience against climate change challenges, especially drought.

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