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Seaweed extract-based fertilizer and water stress on potato crops

Fertilizante à base de extrato de algas marinhas e estresse hídrico nas culturas de batata

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ABSTRACT

Seaweed extract-based fertilizers are applied to mitigate the effects of stress on plants. In this study, we evaluated the effects of different concentrations of seaweed extract-based fertilizer and different irrigation depths on potato crops. The Ágata cultivar and the Markies cultivar were used to conduct two experiments simultaneously. A 4 × 4 experimental design was used, with four doses of seaweed extract-based fertilizer (0, 0.5, 1.0, and 4.0 L ha^{-1}) and four irrigation depths (50%, 75%, 100%, and 125% of crop evapotranspiration); each treatment had three replicates. Leaves were collected 67 days after emergence to analyze macronutrients and micronutrients; additionally, the number of stems per plant and physiological variables were assessed. After harvesting, the number and weight of tubers in different classes were recorded. The differences in parameters among treatment groups were determined by analysis of variance using the F-test, and regression analysis was performed when a significant difference was recorded. The results showed that the contents of potassium, phosphorus, magnesium, and calcium in the leaves of the Ágata cultivar were below the optimal levels for the crop, irrespective of the irrigation level and the dose of seaweed extract-based fertilizer applied. The highest irrigation depths at 100% and 125% of crop evapotranspiration were associated with an increase in the number and weight of the large tubers of the Ágata and Markies cultivars.

Index terms: *Solanum tuberosum* L.; plant regulators; nutrition; irrigation depths.

RESUMO

Para mitigar os efeitos do estresse nas plantas, têm sido aplicados fertilizantes foliares à base de extrato de algas marinhas. Objetivou-se avaliar os efeitos de diferentes concentrações de fertilizante à base de extrato de algas marinhas e lâminas de irrigação na cultura da batata. Dois experimentos foram conduzidos simultaneamente, um com a cultivar Ágata e outro com a cultivar Markies. O delineamento experimental utilizado foi 4 × 4, com quatro doses de fertilizante à base de extrato de algas marinhas (0; 0,5; 1,0 e 4,0 L ha^{-1}) e quatro lâminas de irrigação (50%, 75%, 100% e 125% da evapotranspiração da cultura), com três repetições. Aos 67 dias após a emergência foram coletadas folhas para análise de macro e micronutrientes e, também avaliaram-se: número de hastes por planta e variáveis fisiológicas. Após a colheita, avaliaram-se: número e peso dos tubérculos de diferentes classes. Os dados foram submetidos à análise de variância por meio do teste F e análise de regressão foi realizada quando houve diferença significativa. Os teores de potássio, fósforo, magnésio e cálcio nas folhas da cultivar Ágata ficaram abaixo dos níveis ótimos para a cultura, independente do nível de irrigação e da da dose de fertilizante aplicado. O fertilizante reduziu os efeitos do estresse hídrico, aumentando a eficiência fotoquímica das plantas de batata Markies. As maiores lâminas de irrigação em 100% e 125% da evapotranspiração da cultura levaram ao aumento do número e peso de tubérculos grandes para as cultivares Ágata e Markies.

Termos para indexação: *Solanum tuberosum* L.; reguladores de plantas; nutrição; profundidades de irrigação.

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Introduction

Potato (*Solanum tuberosum* L.) is a primary crop cultivated and consumed around the world (Zhou et al., 2019). It is popular mainly due to its nutritional properties and serves as a major source of carbohydrates, phosphorus, and B vitamins, which make potatoes a key contributor to global food security (International Potato Center- CIP, 2019).

Potato plants have a shallow and less extensive root system, which makes them susceptible to water stress. Therefore, they need to be irrigated to optimize yield and tuber quality, (Marcomini, 2020).

Water deficit during potato cultivation can cause morphological changes that may influence photosynthetic efficiency, and consequently, tuber yield; moreover, water deficit may induce the development of pear-shaped tubers, due to differences in growth, or even tubers with a hollow center

(Vayda, 1994). In the phenological stage known as tuberization, the duration and severity of water stress strongly influence the development and production of tubers. When water stress occurs during emergence and/or tuberization, which are the most critical periods, it decreases plant growth and productivity, shortens the cycle, and reduces the number and size of tubers (Monneveux et al., 2013).

The application of new technologies in recent years has led to a considerable increase in the yield of various crops. In potato cultivation, the factors contributing to higher production include the use of adapted varieties, proper application of fertilizers, soil amendments, effective pest and disease management, and the application of biostimulants and foliar fertilizers (Backes et al., 2017).

Several researchers have investigated the use of various effective and feasible biostimulants to decrease the burden of chemicals (fertilizers and pesticides) on agricultural soils and crops (Souri & Hatamian, 2019; Noroozlo, Souri, & Delshad, 2019; Souri & Bakhtiarizadeh, 2019).

Studies on seaweed extract-based fertilizers found that their components are easily recognized by plant cells; thus, these fertilizers can effectively regulate the growth and development of plants (Franceschini et al., 2010) and enhance plant tolerance to numerous stress factors (Shukla et al., 2019). However, only a few studies on potato cultivation with foliar fertilizer application have investigated the effects of water deficiency. Thus, in this study, we assessed the effects of different doses of seaweed extract-based fertilizer and irrigation depths on the growth of potato crops.

Material and Methods

The Ágata potato cultivar and the Markies cultivar were used to conduct two experiments simultaneously in a greenhouse at the Universidade Federal (18°43′36″S, 47°31′31″W; 900 m altitude), Monte Carmelo Campus, MG, Brazil, located in the mesoregion of Triângulo Mineiro and Alto Paranaíba.

In both experiments, a randomized complete block design (RCBD) was implemented, using a 4 × 4 factorial arrangement with three replicates. The plants were treated with a combination of four concentrations of seaweed extract-based fertilizer (0 L ha^{-1}, 0.5 L ha^{-1}, 1.0 L ha^{-1}, and 4.0 L ha^{-1}) and four irrigation depths [50%, 75%, 100%, and 125% of crop evapotranspiration (ETc)]. Each experimental plot consisted of three pots spaced 1.0 m apart in rows, and a gap of 0.30 m was maintained between pots. Each pot contained two plants, and both were evaluated.

The seed tubers of the Ágata cultivar were second generation and those of the Markies cultivar were third generation. Both cultivars belonged to category III, i.e., the seed tubers were 30–40 mm in diameter. The tubers were donated by Agro Soczek Agricultural Ltd.

Planting was conducted on June 24, 2022, in plastic pots with a capacity of 8.5 L. Before planting, the soil was sampled, and its chemical and physical properties were analyzed. The results indicated that the soil composition was as follows: clay = 74.5%; pH of $CaCl_2$ = 4.8; P meh = 0.7 mg dm^{-3}; K = 0.08 cmolc dm^{-3}; Ca = 0.16 cmolc dm^{-3}; Mg = 0.04 cmolc dm^{-3}; Zn = 0.6 mg dm^{-3}; B = 0.08 mg dm^{-3}; Fe = 24 mg dm^{-3}; Cu = 0.6 mg dm^{-3}; Mn = 8.2 mg dm^{-3}; H+Al = 2.50 cmolc dm^{-3}; Al = 0.3 cmolc dm^{-3}; SB = 0.28 cmolc dm^{-3}; T = 2.78 cmolc dm^{-3}; V% = 10%.

Thirty days before planting, 5.34 g of limestone with a PRNT of 90% was applied to each pot to increase the base saturation to 60% (Ribeiro, Guimarães, & Alvarez, 1999), equivalent to 1.54 t ha^{-1} for a 20 cm layer. For fertilization, the 04–28–08 formulation was used at a dosage of 7 g per pot, corresponding to 1,650 kg ha^{-1}; the formulation contained 4% nitrogen, 28% phosphorus expressed as P_2O_5, 8% potassium expressed as K_2O, 10% calcium, 7.2% sulfur, 0.03% boron, 0.05% manganese, and 0.1% zinc.

For top-dressing fertilization, the 12–00–12 formulation was used, which contained 12% nitrogen, 12% potassium expressed as K_2O, 14% calcium, and 0.2% boron. These were applied 33 and 54 days after planting, respectively, at a dosage of 3.3 g per pot (520 kg ha^{-1}) and 2.2 g per pot (340 kg ha^{-1}) (Ribeiro, Guimarães, & Alvarez, 1999).

The seaweed extract-based fertilizer (YaraVita BiotracTM, Yara®) used in the study consisted of 5.6% nitrogen as urea, 2.3% potassium as potassium citrate, 1.1% zinc as zinc sulfate, 1.1% boron as boron monoethanolamine, 10% total organic carbon, 2.7% *Ascophyllum nodosum* algae extract, 9.4% stabilizer, 0.4% surfactant, and water. A single foliar application of this fertilizer was performed 19 days after emergence (DAE), in the morning using a hand-held sprayer with a 2-L tank capacity. Approximately 0.8 L of fertilizer was used for each set of 12 plots, resulting in an application rate of 150 L ha^{-1}. The doses applied were based on the manufacturer's recommendations (1–3 L ha^{-1}); lower and higher doses were established relative to the recommended dose. A setup was also established with no fertilizer applied, to verify the behavior of the plants at different doses.

The irrigation system used was the NetBow drip arc. Before starting tuberization, irrigation was maintained at 100% of the crop evapotranspiration, according to the matrix potential for potato cultivation, which is -30 to -50 kPa (De Albuquerque, 2010). After tuberization started, different irrigation depths were established for each treatment. For the irrigation control setup, soil moisture content in some pots was measured using tensiometers. The potential or water content in the soil was measured daily at six representative points in the area, which were located in the zone of maximum root activity.

After 26 days of application of the seaweed extract-based fertilizer, along with the hilling process (Ribeiro, Guimarães, & Alvarez, 1999), the third leaf from the apical tuft was collected, for a total of six leaves per plot. The leaves were cleaned and dried in an oven at 65 ± 5 °C before the macronutrient [nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S)] and micronutrient [boron (B), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn)] contents were determined.

On the same day that the leaves were collected to conduct leaf analysis, the number of stems per plant and the physiological variables were also assessed by evaluating transient OJIP chlorophyll a fluorescence, including the initial fluorescence (Fo), variable fluorescence (Fv), maximum fluorescence (Fm), maximum quantum yield (Fv/Fm), amount of photons absorbed by the antenna complex (ABS/RC), amount of energy flowing through the antenna complex and captured by the PSII reaction center (TRo/RC), and amount of non-photochemical energy dissipated (DIo/RC). These variables were measured using the PSI Fluorometer (Photon Systems Instruments; model FP100), and readings were obtained from the second true leaf of five plants in each plot between 00:00 a.m. and 03:00 a.m. to ensure that the plants were dark-adapted. The chlorophyll a index was assessed on the same day using Falker's CFL1030 Chlorophyll Meter, taking five readings per plot on the second true leaf from 11:00 a.m. to 3:00 p.m.

The crop was harvested at 67 DAE, and the following parameters were evaluated in the Phytotechnics Laboratory: number and weight of tubers in different classes, based on their cross-sectional diameter: jumbo (larger than 70 mm), extra large (42–70 mm), large (33–42 mm), medium (28–33 mm), small (up to 28 mm), and cull (damaged tissue with no commercial value).

All data were tested for the assumptions of analysis of variance, including the normality of residuals, homogeneity of variances, and additivity at a 5% significance level. When the assumptions were not met, the data were log-transformed. Once the assumptions were met, the data were evaluated via analysis of variance using the F-test at a 5% significance level. When significant differences were found, the data were used to perform regression analysis. All analyses were performed using the R software (R Core Team, 2023).

Results and Discussion

The interaction between the doses of seaweed extract-based fertilizer and irrigation depths was not significant for any of the evaluated foliar nutritional contents. However, for the Ca content in the Ágata cultivar, significant interactions were found between doses of seaweed extract fertilizer within the 100% ETc level (Figure 1a) and the irrigation depths within the 1 L ha^{-1} dose of seaweed extract fertilizer (Figure 1b); significant interactions were also recorded for the Cu content in the Markies cultivar between the doses of seaweed extract fertilizer within the 75% ETc level (Figure 2a) and the irrigation depths within the 4 L ha^{-1} dose of seaweed extract fertilizer (Figure 2b).

In the Ágata cultivar, a quadratic effect was recorded for the doses of seaweed extract-based fertilizer, with a decrease in Ca levels starting from a dose of 1.33 L ha^{-1} (Figure 1a). However, in the Markies cultivar, no significant difference in the leaf Ca content for any of the factors was recorded when evaluated individually.

Although the seaweed extract-based fertilizer contributed to an increase in the Ca content of the Ágata cultivar, the values obtained were below those recommended for the crop, according to Ribeiro, Guimarães and Alvarez (1999). Although the Ca content increased by 2.38 g kg^{-1} with an increase in water availability in the substrate (Figure 1a), the nutrient content in the Ágata cultivar was also below the range considered adequate for the crop (76–100 g kg^{-1}), according to Ribeiro, Guimarães and Alvarez (1999). Liming and fertilization, using Ca-containing formulations, did not meet the cultivar's requirements, as the initial amount of Ca present in the soil was extremely low.

Moreover, the Ca levels were below the ideal level probably because the leaf analysis was conducted earlier than recommended for the state of Minas Gerais; it is generally conducted at the time of hilling, i.e., around 45 days after planting (Faquin, 2002). However, the early leaf collection in this experiment is justified, as it was conducted to investigate whether the seaweed extract-based fertilizer could enhance nutrient uptake by the plant.

In the Markies cultivar, the Cu content differed significantly only for seaweed extract-based fertilizer within the 75% ETc level (Figure 2a) and for the irrigation depths at a dose of 4 L ha^{-1} seaweed extract-based fertilizer (Figure 2b). For the doses of seaweed extract-based fertilizer within the 75% ETc level, the increase in Cu content was linear (Figure 2a), and for each increase in 1 L ha^{-1} foliar fertilizer, the Cu content increased by 3.13 mg kg^{-1}, keeping the levels within the adequate range for potato cultivation. In contrast, the irrigation depth at a dose of 4 L ha^{-1} seaweed extract-based fertilizer positively influenced leaf Cu levels up to a level of 77.74% ETc, after which, the Cu levels decreased (Figure 2b). However, irrespective of the irrigation depth, Cu levels were within the range considered to be adequate for the crop. Soratto, Fernandes and Souza-Schlick (2011) stated that the absorption of Cu increases starting from 64 days after planting until the end of the potato crop cycle.

For the Ágata cultivar, the Cu content increased with an increase in the dose of seaweed extract-based fertilizer, but it remained within a sufficient range at all doses applied. In the absence of fertilizer treatment (0 L ha^{-1}), the content was 12.06 mg kg^{-1}, whereas, at a dose of 4 L ha^{-1}, the content was 16.44 mg kg^{-1}. From a dose of 0 L ha^{-1} to 0.5 L ha^{-1}, the Cu level increased by 0.59 mg kg^{-1}, whereas, from a dose of 1.0 L ha^{-1} to 4 L ha^{-1}, the Cu level increased by 3.19 mg kg^{-1} (Figure 3). Although the algal extract-based fertilizer did not contain Cu, the plant protection products may have influenced changes in the Cu content in the leaf.

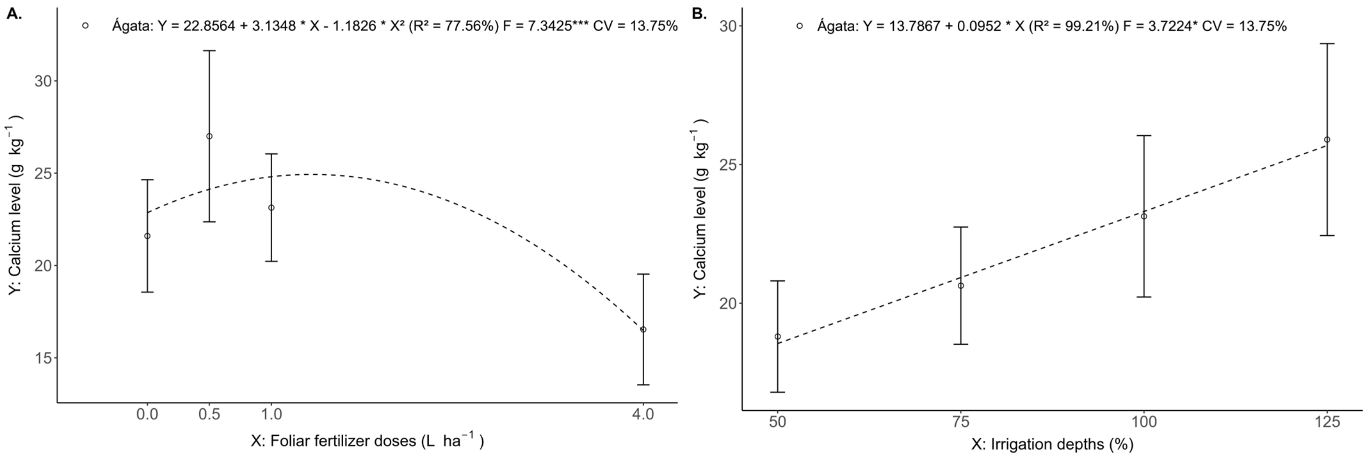

Figure 1: The results of the interaction between the doses of seaweed extract-based fertilizer at 100% ETc irrigation depth (a) and irrigation depths at a dose of 1 L ha^{-1} of algal extract-based fertilizer (b) for Ca levels in potato leaves of the Ágata cultivar.

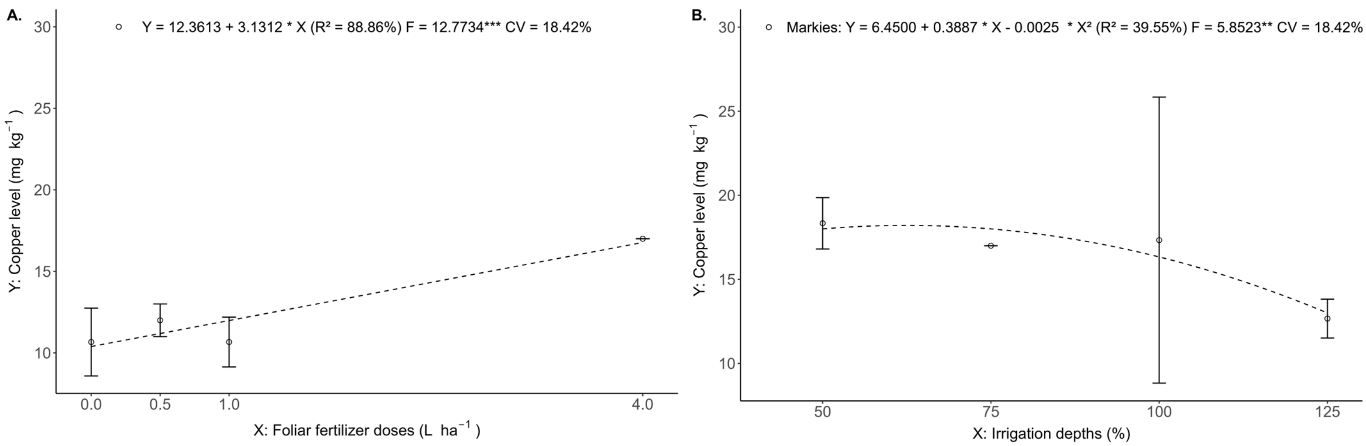

Figure 2: The results of the interaction between the doses of seaweed extract-based fertilizer at the 75% ETc irrigation depth (a) and irrigation doses of 4 L ha^{-1} of seaweed extract-based fertilizer (b) for the average Cu content in potato leaves of the Markies cultivar.

For both cultivars, no significant differences in N, S, and Fe content were recorded for any of the factors evaluated individually. Similar findings were recorded for the P (Figure 4) and K (Figure 5) levels in the Markies cultivar. In the Ágata cultivar, increasing the irrigation depths up to 125% ETc led to an increase in the contents of P and K (Figures 4 and 5). However, their levels were below the required range for the crop, according to Ribeiro, Guimarães and Alvarez (1999), who established that the sufficient doses of P and K are 2.9–5.0 g kg^{-1} and 93–115 g kg^{-1}, respectively.

Similar results were obtained by Pilon, Soratto and Moreno (2011), who evaluated the effect of water deficiency on potatoes and found that the K content was higher in plants that had adequate water supply compared to the plants in the control treatment.

The P and K contents in the Ágata cultivar increased with an increase in the irrigation depth up to 125% ETc, probably because of the growth-promoting effects of algal extracts, which decreased the water deficit, as reported by Pedro et al. (2022).

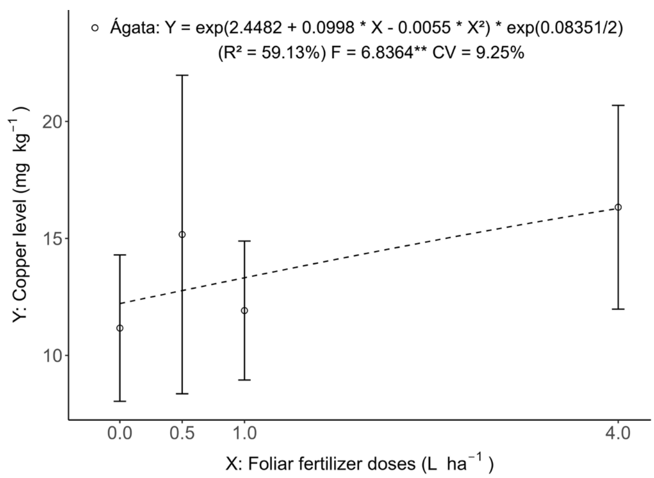

Figure 3: The average Cu content in potato leaves of the Ágata cultivar as a function of different doses of seaweed extract-based fertilizer.

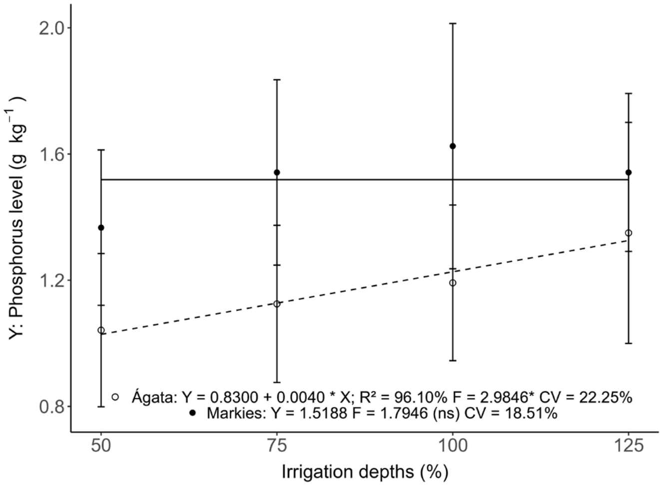

Figure 4: The average P content in potato leaves of the Ágata and Markies cultivars as a function of different irrigation depths.

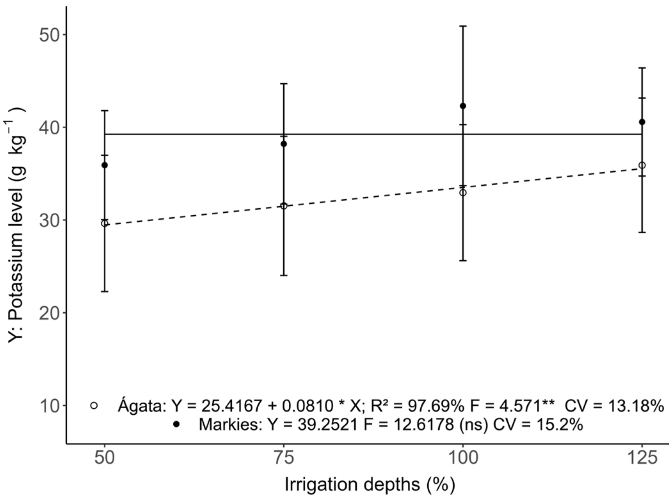

Figure 5: The average K content in potato leaves of the Ágata and Markies cultivars as a function of different irrigation depths.

The low levels of P recorded in the Ágata cultivar may be related to its adsorption power. Klein and Agne (2012) found that the fertilizer added to the soil has low water solubility and high interaction with soil particles. As the fertilizer primarily moves through diffusion, the process becomes slow and depends on soil moisture.

Potassium (K) is the nutrient most absorbed by potatoes; it increases the yield and improves tuber quality (Singh, & Lal, 2012). Sufficient levels of P and K need to be available for maximum crop yield, given that potatoes absorb approximately 78% of P and 68% of K from the soil; these nutrients accumulate in the tubers (Fernandes & Soratto, 2012).

For Mg content, a quadratic effect of the doses of seaweed extract-based fertilizer was recorded. A reduction of 1.88 L ha^{-1} in the Mg content was recorded for the Ágata cultivar, but no effect on the Mg content was recorded for the Markies cultivar (Figure 6a). An increase in the irrigation depth had an increasing linear effect on Mg levels for both cultivars (Figure 6b); however, for the Markies cultivar, the values were above the recommended level for the crop at a dose of 56.90% of ETc. For the Ágata cultivar, the Mg levels were below those recommended for the crop (i.e., below 1.0–1.2 g kg^{-1}), according to Ribeiro, Guimarães and Alvarez (1999).

Magnesium (Mg) acts as a modulator of the Rubisco enzyme and facilitates the interaction between nutrients and enzymes. Sufficient levels of Mg in the plant lead to greater stability in binding, and thus, it increases the affinity for CO_2 (Rodrigues et al., 2022).

The levels of B and Zn in the leaves differed significantly only between the doses of the algal extract-based fertilizer, for the Ágata and Markies cultivars (Figures 7a and b).

Foliar B content increased with an increase in the dose of seaweed extract-based fertilizer in both cultivars (Figure 7a); the B levels were higher than those considered adequate by Ribeiro, Guimarães and Alvarez (1999) (25–50 mg kg^{-1}).

This result can be explained by the concentration of B in the seaweed extract-based fertilizer applied in this study; an increase in the dose of the fertilizer applied contributed to greater absorption of B by the plants. Additionally, planting and top dressing may have altered the nutritional balance of the plant, resulting in an excess of nutrients. Another reason, according to Carvalho et al. (2018), might be that the seaweed extract-based fertilizer (*Ascophyllum nodosum*) acted as a B chelating agent and influenced the nutrient uptake in a linear fashion.

The results of soil analysis before planting showed that B levels were extremely low. Boron (B) is required for potato cultivation, particularly during the early stages of tuber formation. They promote the growth and division of meristematic tissues, the development of the cell wall, and the translocation of starch from the aerial parts to the tubers (Cabalceta, Saldias, & Alvarado, 2005).

The application of 0, 0.5, 1.0, and 4 L ha^{-1} doses of seaweed extract-based fertilizer showed that the Zn content in the leaves was 9.47, 21.58, 41.79, and 72.58 mg kg^{-1} for the Markies cultivar, respectively (Figure 7b). However, for the Ágata cultivar, all treatments showed Zn levels within the adequate range for the crop (Figure 7b). These levels of Zn occurred probably because the fertilizer based on seaweed extract applied contained 1.1% Zn. Additionally, the Zn content in the soil was in the medium range, which might have also contributed to the increase in Zn levels in the aerial parts of the plants.

Zinc, iron, copper, and manganese act as enzyme activators that increase the plant's metabolic activity. The increase in enzymatic activity, in the presence of plant hormones, increases the emission of chemical signals, favoring cell division and expansion, thus resulting in greater vegetative growth (Taiz et al., 2017). Therefore, high levels of these nutrients increase the synthesis and translocation of metabolites, thus enhancing productivity (Povero et al., 2016).

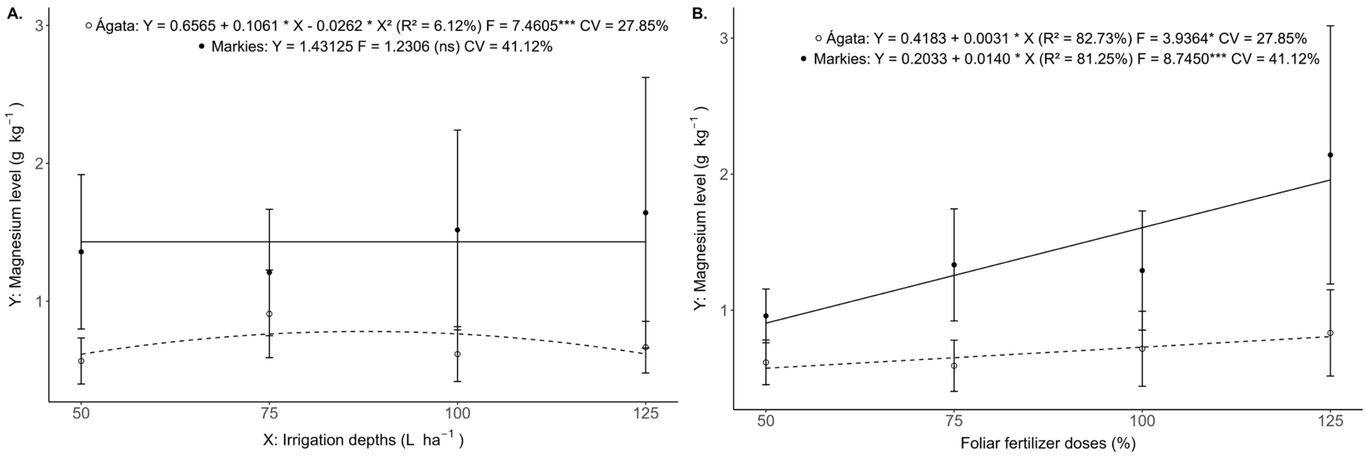

Figure 6: The average Mg content in the potato leaves of the Ágata and Markies cultivars as a function of different doses of seaweed extract-based fertilizer (a) and irrigation depth (b).

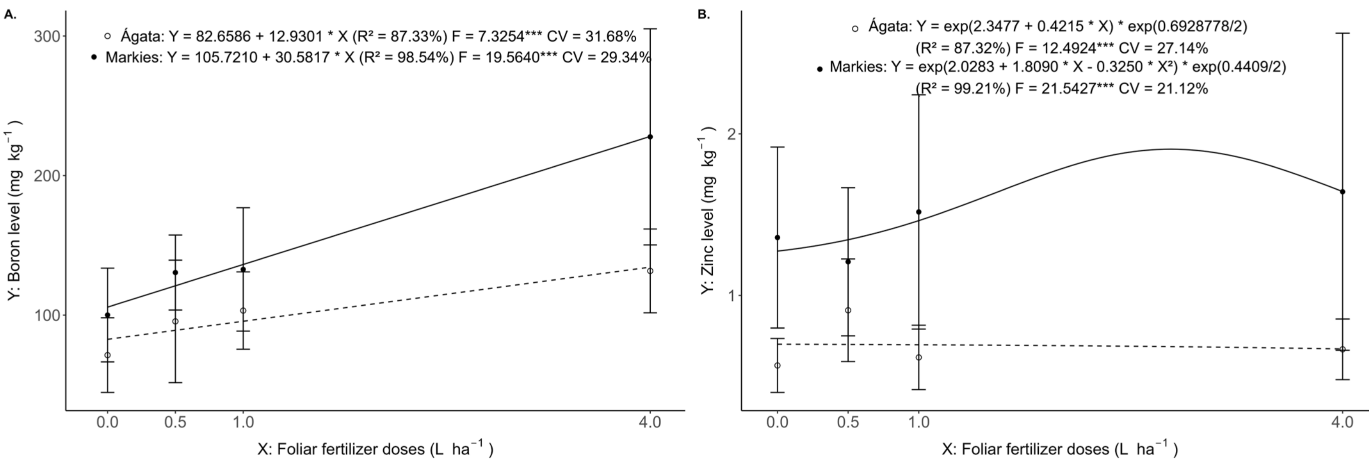

Figure 7: The average levels of B (a) and Zn (b) in potato leaves of the Ágata and Markies cultivars as a function of different doses of the algal extract-based fertilizer.

The Mn content was significantly different only for irrigation depths, for both cultivars. In the Ágata cultivar, the Mn content in the leaves decreased up to the 82.5% ETc level, which corresponded to a leaf Mn content of 51.44 mg kg^{-1}, followed by a subsequent increase (Figure 8). For the Markies cultivar, an increasing linear effect was found with increasing irrigation depths (Figure 8); however, for all irrigation depths, the nutrient levels remained within the range considered adequate for the crop, which was 30–250 mg ha^{-1} (Ribeiro, Guimarães, & Alvarez, 1999).

The results obtained were similar to the findings of Soratto, Fernandes and Souza-Schlick (2011), who showed that large amounts of Mn accumulate in the leaves and stems of potato plants and perform various functions in metabolism, such as activating enzymes in the respiration process and water photolysis during photosynthesis (Cabalceta, Saldias, & Alvarado, 2005).

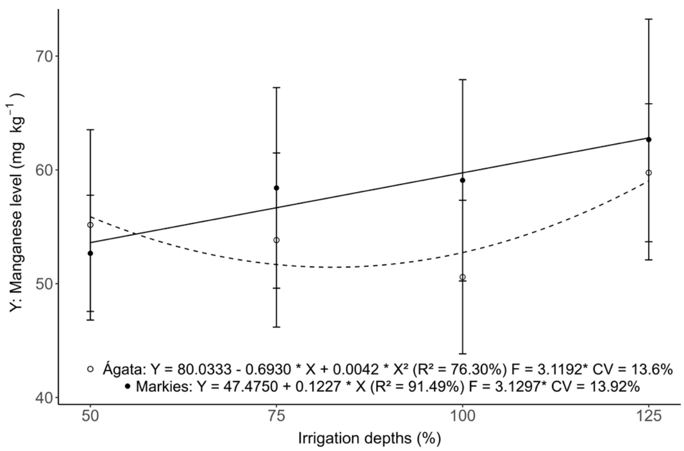

Figure 8: The average Mn content in potato leaves of Ágata and Markies cultivars as a function of different irrigation depths.

Additionally, high levels of Mn might accumulate due to its low mobility in plant tissues.

For physiological characteristics, no significant interaction was observed between the doses of seaweed extract-based fertilizer and irrigation doses; additionally, no significant difference was found between the levels of the isolated factors for the Ágata cultivar. For the Markies cultivar, no significant interaction was observed between the dose of seaweed extract-based fertilizer and the irrigation depth; moreover, no significant difference was recorded between the levels of the isolated factors for the physiological characteristics of initial fluorescence (F_0), variable fluorescence (Fv), maximum fluorescence (Fm), and maximum quantum yield (Fv/Fm).

For the amount of photons absorbed by the antenna complex (ABS/RC), the amount of energy dissipated by non-photochemical dissipation (DIo/RC), and the amount of energy that flows through the antenna complex and is captured by the PSII reaction center (TRo/RC), significant interactions were observed between the doses of seaweed extract-based fertilizer and irrigation doses for the Markies cultivar. We also found a significant difference between the doses of seaweed extract-based fertilizer at 100% ETc irrigation depth and irrigation depths in the absence of seaweed extract-based fertilizer (0 L ha^{-1}) for the following variables: amount of photons absorbed by the antenna complex (ABS/RC) (Figure 9), dissipated energy flow per reaction center (Dlo/RC) (Figure 10), and energy capture flow per active reaction center (TRo/RC) (Figure 11).

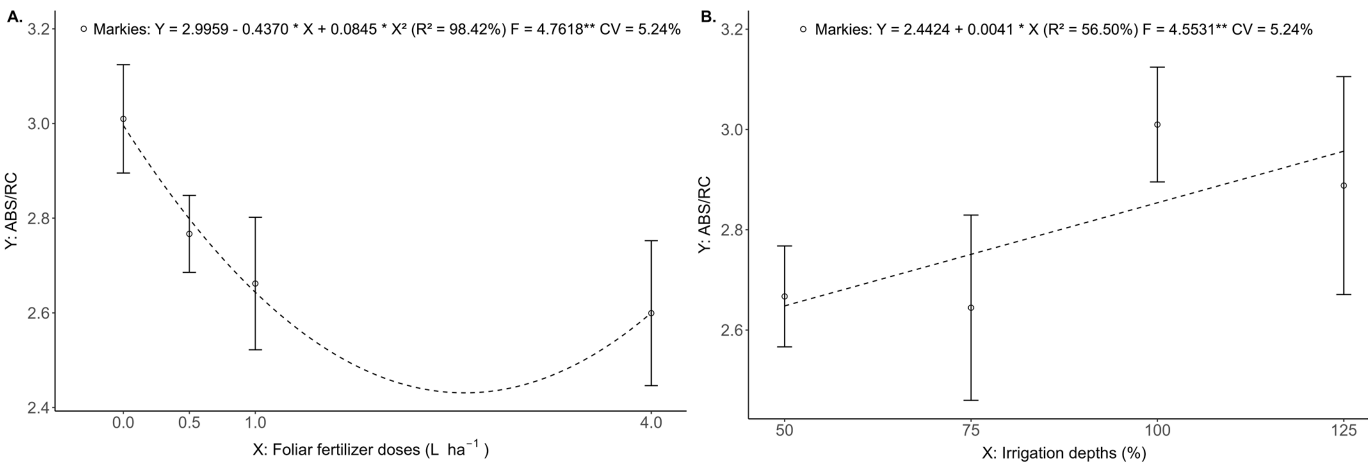

Figure 9: The results of the interaction between the doses of seaweed extract-based fertilizer at 100% ETc irrigation depth (a) and irrigation depths at a dose of 4 L ha^{-1} seaweed extract-based fertilizer (b) for the amount of photons absorbed by the antenna complex (ABS/RC) in the Markies potato cultivar.

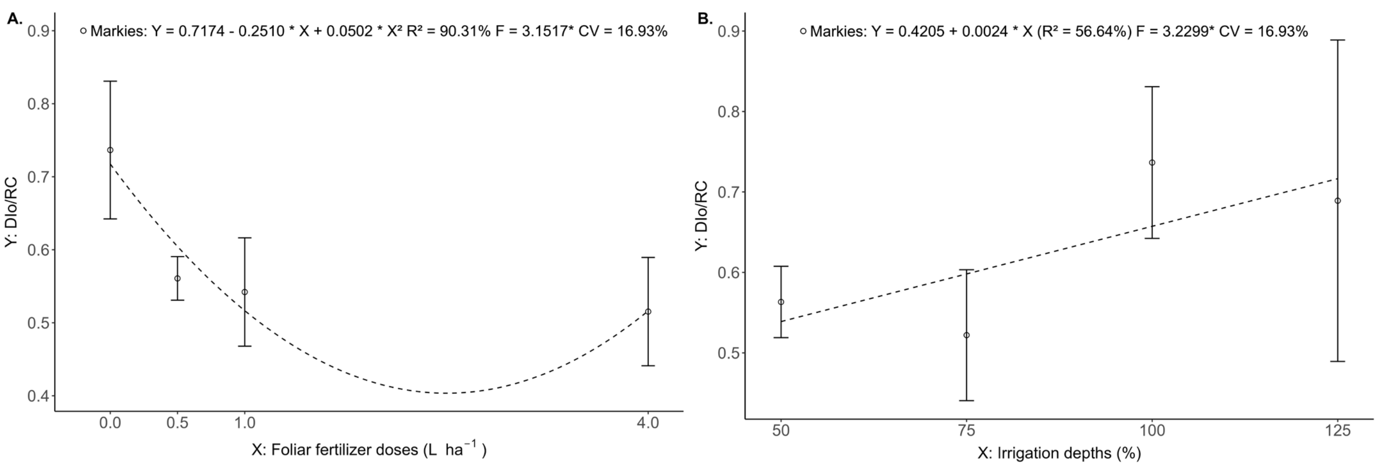

Figure 10: The results of the interaction between the doses of seaweed extract-based fertilizer at 100% ETc irrigation depth (a) and irrigation depths at a dose of 4 L ha^{-1} seaweed extract-based fertilizer (b) for dissipated energy flow per reaction center (Dlo/RC) in potato plants of the Markies cultivar.

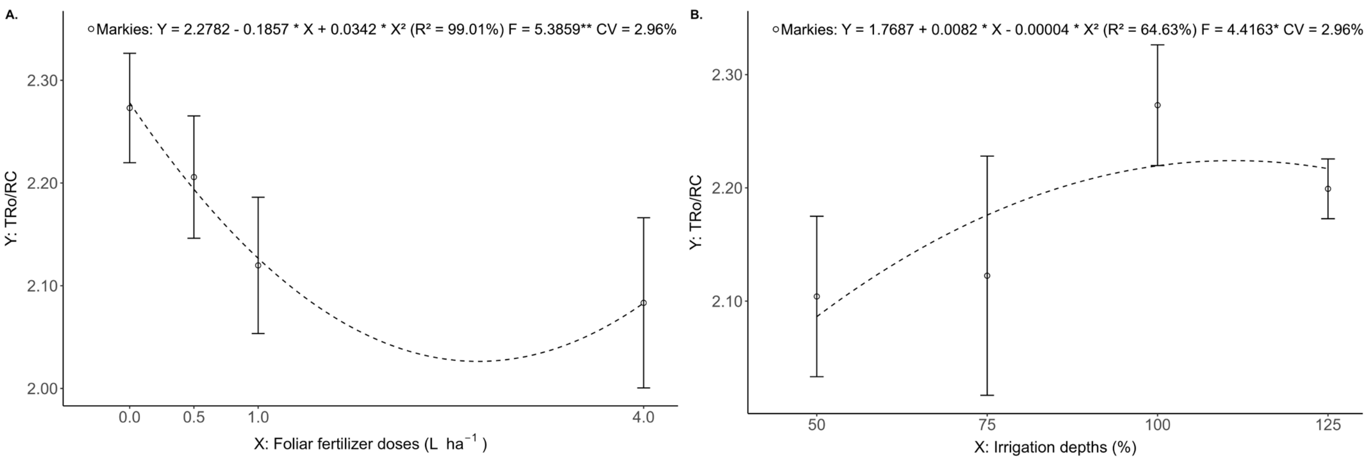

Figure 11: The results of the interaction between the doses of seaweed extract-based fertilizer at 100% ETc irrigation depth (a) and irrigation depths at a dose of 4 L ha^{-1} seaweed extract-based fertilizer (b) for energy capture flux per active reaction center (TRo/RC) in Markies potato plants.

The quadratic model best described the amount of photons absorbed by the antenna complex (ABS/RC) associated with the interaction between the doses of seaweed extract-based fertilizer and the 100% ETc irrigation depth. The model showed that the value of ABS/RC decreased until a dose of 2.58 L ha^{-1}, and then, the value increased (Figure 9a). In contrast, irrigation depths positively influenced ABS/RC when fertilizer treatment was absent (0 L ha^{-1}) (Figure 9b).

The high ABS/RC levels absorbed by Markies potato plants at a dose of 4 L ha^{-1} of seaweed extract-based fertilizer and the increase in the amount of photons absorbed as irrigation depths increased indicated that photoinhibition did not damage the photosystem. The antenna system, which is responsible for capturing energy from the light that reaches the plant, increases in plants under stress to compensate for the loss of energy that occurs under stress due to disorders in photosystem II (Martinazzo et al., 2013).

For the dissipated energy flow per reaction center (DIo/RC), the dissipation of energy flow decreased with the application of seaweed extract-based fertilizer; the lowest energy dissipation was recorded at a fertilizer dose of 2.5 L ha^{-1} (Figure 10a), after normalizing the PSII of the plants. Kissi et al. (2020) showed that when the DIo/RC value is high, a large part of the absorbed energy is dissipated as heat or fluorescence, which can be observed in the potato plants of the Markies cultivar in the absence of fertilizer treatment (Figure 10a).

This finding implied that applying the seaweed extract-based fertilizer decreased damage to the PSII of Markies potato plants. Plants that are not harmed by absorption fluxes do not experience increased heat dissipation, as this increase is associated with the inactivation of PSII and a decrease in photochemical energy conversion (Guidi, Lo Piccolo, & Landi, 2019).

When examining the effects of irrigation depths in DIo/RC, the plants exhibited greater energy dissipation at an irrigation depth of 125% ETc (Figure 10b). This occurred probably because the plants in this condition suffered from excess water in the soil.

The Dlo/RC is a parameter that clarifies the integrity of PSII, as the energy that is not transported to the photochemical phase of photosynthesis is dissipated, at the risk of increasing the number of free electrons, which can give rise to reactive oxygen species, potentially enhancing oxidative stress (Taiz et al., 2017).

The TRo/RC showed a similar effect to that of the Dlo/RC, i.e., the dose of seaweed extract-based fertilizer reduced the effects of water stress on the plants (Figure 11a). However, a quadratic increase in the TRo/RC values was recorded up to 102.5% ETc irrigation depth (Figure 11b), which corresponded to a value of 2.18 for TRo/RC. Martinazzo et al. (2013) evaluated water stress in plum plants (*Prunus salicina*) and reported an increase in the values of Dlo/RC and TRo/RC. The authors stated that the increase in TRo/RC values indicated an increase in energy flow captured by the RC (reaction center) in plants under water stress. They also stated that the increase in TRo/RC was justified by an increase in the amount of dissipated energy (DIo/RC).

The plants adapted better to water stress after the fertilizer was added due to the increase in their defense mechanism against reactive oxygen species (ROS), increase in photosynthetic activity, chlorophyll content, and nutrient uptake, decrease in photoinhibition of PSII, lipid peroxidation, and oxidative damage to tissues; these changes delayed leaf senescence and improved leaf stomatal conductance (Shukla et al., 2017).

For the effective quantum yield, a significant difference was observed between irrigation depths only for the Markies cultivar, i.e., the effective quantum yield increased with an increase in the irrigation depth (Figure 12).

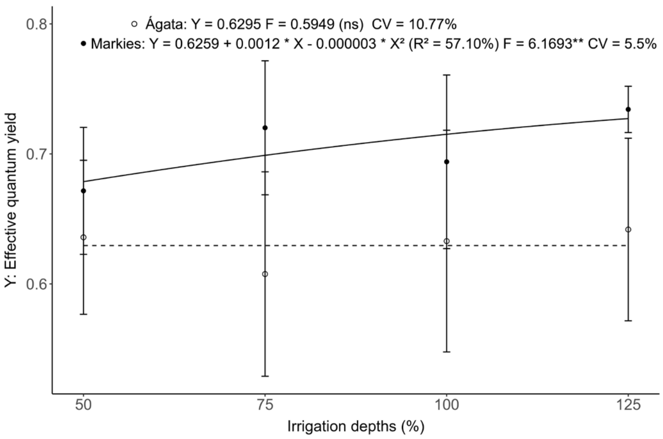

Figure 12: The average effective quantum yield values in potato plants of the Ágata and Markies cultivars as a function of different irrigation depths.

The effective quantum yield values were similar to those reported in previous studies for the highest applied water depths. Maxwell and Johnson (2000) found that under normal conditions, the effective quantum yield of plants ranges between 0.75 and 0.85, and a decrease in the parameter indicates that the plant is under stress. Irrigation depths of 50% and 75% of ETc resulted in greater stress on the plants, which was justified by the values obtained for DIo/Rc and TRo/RC (Figure 12). Lower irrigation depths resulted in a lower quantum yield of PSII as a result of an increase in sensitivity due to water deficiency.

Damage to PSII depends on the duration of exposure of the plant to water stress, which can cause severe damage to the plants, thus limiting their photosynthetic potential (Pieruschka et al., 2012). Liu et al. (2011) found that exposure to water stress may induce a photoinhibitory effect, which can lead to disturbances in the reaction centers of PSII. These changes can decrease the photochemical efficiency of PSII, as water acts as an electron donor for the fixation of atmospheric CO_2.

No significant interaction was observed between the doses of foliar fertilizer based on seaweed extract and irrigation depths for the number and weight of tubers in any of the potato classes. However, a significant interaction was found between the evaluated factors for the number of stems in the Markies cultivar.

The interaction showed a significant difference for the foliar fertilizer doses across irrigation depths of 50% (Figure 13a), 75% (Figure 13b), 100% (Figure 13c), and 125% of ETc (Figure 13d), and also for irrigation depths at a dose of 1 L ha^{-1} of seaweed extract-based fertilizer (Figure 13e).

For irrigation levels of 50%, 75%, and 100% ETc, the number of stems of the Markies cultivar decreased with an increase in the dose of seaweed extract-based fertilizer applied (Figures 13a, b, and c).

For an irrigation depth of 125% ETc, across all doses of seaweed extract-based fertilizer, there was an observed adjustment to the quadratic model, according to which, the number of stems decreased up to a dose of 2.34 L ha^{-1}, followed by an increase (Figure 13d).

When 1 Lha^{-1} seaweed extract-based fertilizer was applied, the number of stems decreased up to an irrigation depth of 66.64% ETc, followed by a subsequent increase (Figure 13e). For the Ágata cultivar, although no interaction was found between the factors for the number of stems, a significant difference was found between the doses of seaweed extract-based fertilizer (Figure 14).

A quadratic effect was found on the number of stems for the Ágata cultivar; the value increased up to a dose of 2.46 L ha^{-1} of the seaweed extract-based fertilizer with an average number of stems of 4.6, followed by a subsequent decrease (Figure 14).

The number of stems per plant increased probably due to the effect of the compounds present in the foliar fertilizer applied (cytokinins). Oliveira et al. (2011) showed that even when seaweed extract-based fertilizer is applied in small quantities, plants respond satisfactorily, i.e., their cell division increases, and consequently, their aerial parts develop.

Andrade et al. (2018) reported that the application of extracts from algae of the species *Ascophyllum nodosum* can decrease abiotic stress.

Friedrich et al. (2020) assessed the effect of biostimulants on the production of beet seedlings and found that biostimulants increased the length of the largest leaf on the seedlings. Biostimulants based on seaweed extract also nourish plants, as they alter the functions of certain membrane proteins, such as Ca and K pumps, which facilitate the transport of solutes within cells, thereby enhancing ionic transport, and consequently, the uptake of nutrients (Taiz et al., 2017).

No significant difference was recorded among the doses of the seaweed extract-based fertilizer for either the variable number of tubers or the tuber weight across any of the classes. However, for irrigation depths, a significant difference was recorded in the number of tubers of the diverse and special classes for the Ágata and Markies cultivars (Figure 15) and the number of tubers of the jumbo class for the Markies cultivar (Figure 16). The number of tubers in the other classes (first, second, and various) did not differ significantly between the irrigation depths applied.

The number of tubers in the large class (42–70 mm) increased with an increase in the irrigation depths (Figure 15a), unlike that observed in the mini class (up to 28 mm), i.e., as the irrigation depth increased, the number of tubers in this class (Figure 15b) decreased for both cultivars.

The potato plant has a low tolerance to water stress due to its shallow and sparsely branched root system, which decreases the transport of photoassimilates when the plant is under water stress (50% ETc). As irrigation depth increases, the number of tubers of the mini class (low commercial value category) decreases; as the transport of photoassimilates in the plant increases due to the opening of the stomata, the quality of the tubers in the other classes of commercial interest improves (Marcomini, 2020).

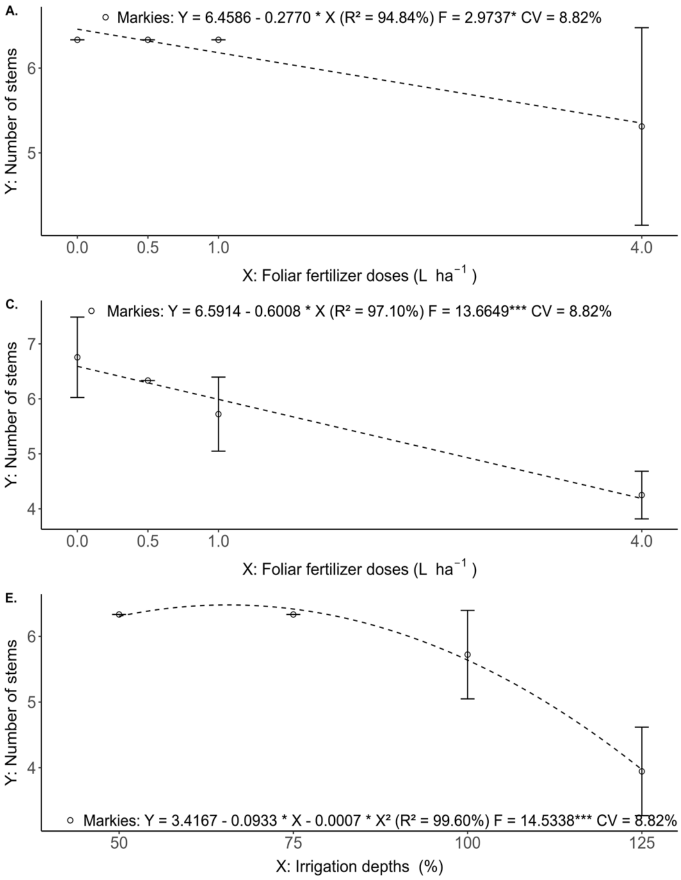

Figure 13: The results of the interaction of the doses of seaweed extract-based fertilizer across irrigation depths of 50% ETc (a), 75% ETc (b), 100% ETc (c), and 125% ETc (d), and irrigation depths at a dose of 1 L ha^{-1} seaweed extract-based fertilizer (e) for the number of stems per plant of the Markies cultivar.

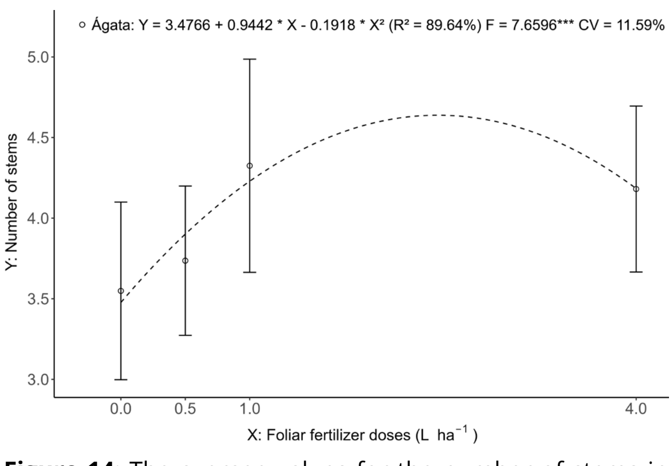

Figure 14: The average values for the number of stems in potato plants of the Ágata cultivar as a function of different irrigation depths.

The quantity of tubers in the jumbo class (>70 mm) increased with an increase in the irrigation volume applied (Figure 16). It is one of the most commercially valuable classes in the market, as it is highly profitable for the farmer; therefore, it has high commercial demand.

Jadoski, Suchoronczek, and Santos (2017) assessed water deficiency at different phenological stages of the potato crop and obtained results similar to those found in this study, in which we found that water deficit in the initial period of the cycle is more detrimental to the productive yield of the crop, as it affects tuberization; thus, water deficit in the early stages limits the productive potential and vegetative development.

The biostimulant doses did not affect the tuber weight in any of the evaluated cultivars. Significant differences were found between irrigation depths for the weight of jumbo class tubers in the Markies cultivar (Figure 17a), the weight of large tubers in the Ágata and Markies cultivars (Figure 17b), and the weight of small tubers in the Markies cultivar (Figure 17c).

The number of tubers of the jumbo class in the Markies cultivar (Figure 17a) and the number of tubers of the large class in both cultivars (Figure 17b) increased linearly with an increase in irrigation water depths. These results highlighted that soil water availability strongly influenced crop development and productive parameters.

Although the number and weight of tubers increased in the special class with the increase in irrigation depths, these values were below normal. The results of the soil analysis conducted before planting showed that nutrient levels were low. Moreover, the addition of nutrients through fertilization and the application of seaweed extract-based fertilizer were probably not sufficient to meet the needs of the plants; this nutrient deficit probably affected the nutritional content, and consequently, the productive parameters of the potato crop.

In the Markies cultivar, only the irrigation depth had a linearly increasing effect on the weight of tubers in the jumbo class up to the 125% ETc irrigation depth (Figure 17c). Mantovani et al. (2013) used a drip irrigation system to determine the effect of different irrigation depths on two sweet potato cultivars and concluded that the yield of sweet potato cultivars significantly depended on the applied water depth. The highest yields were recorded with 95.2% and 100.4% ETc for 'Amanda' and 'Duda', respectively.

Due to the differences in the composition of seaweed extract-based fertilizers, the appropriate use of these products needs to be paid more attention, especially concerning the dose, application stage, and association with pesticides. By identifying the appropriate application parameters, the application of seaweed extract-based fertilizer can maximize the profitability of potato crops.

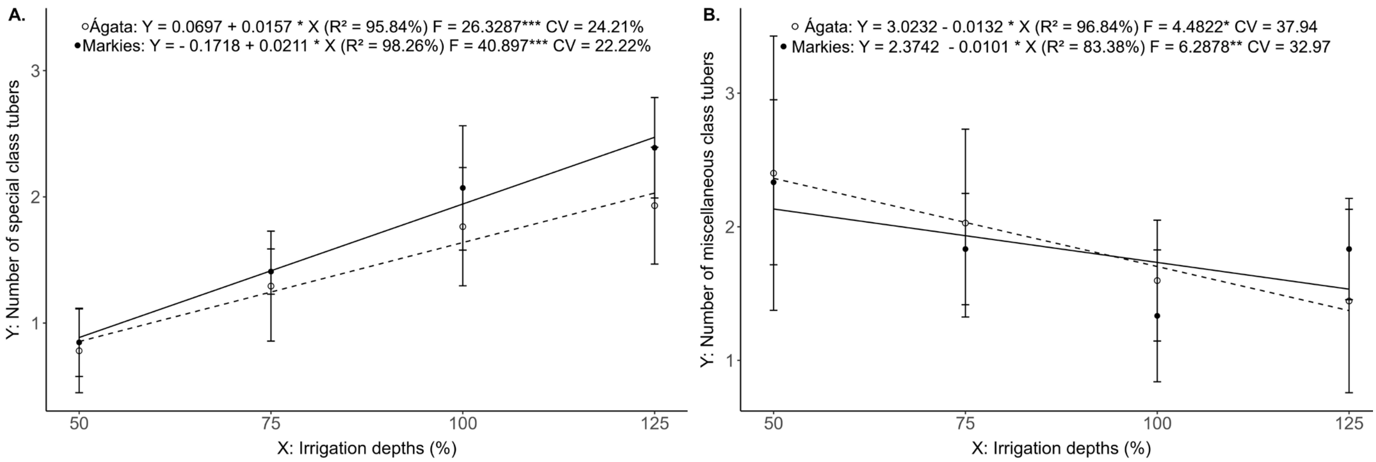

Figure 15: The average values for the number of tubers in the large class (a) and the number of tubers in the mini class (b) in the potato plants of the Ágata and Markies cultivars as a function of different irrigation depths.

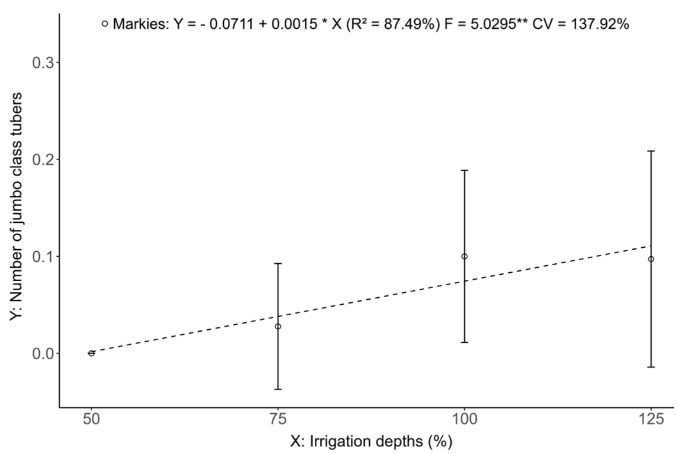

Figure 16: The average values of the number of tubers in the jumbo class for the Markies potato cultivar as a function of different irrigation depths.

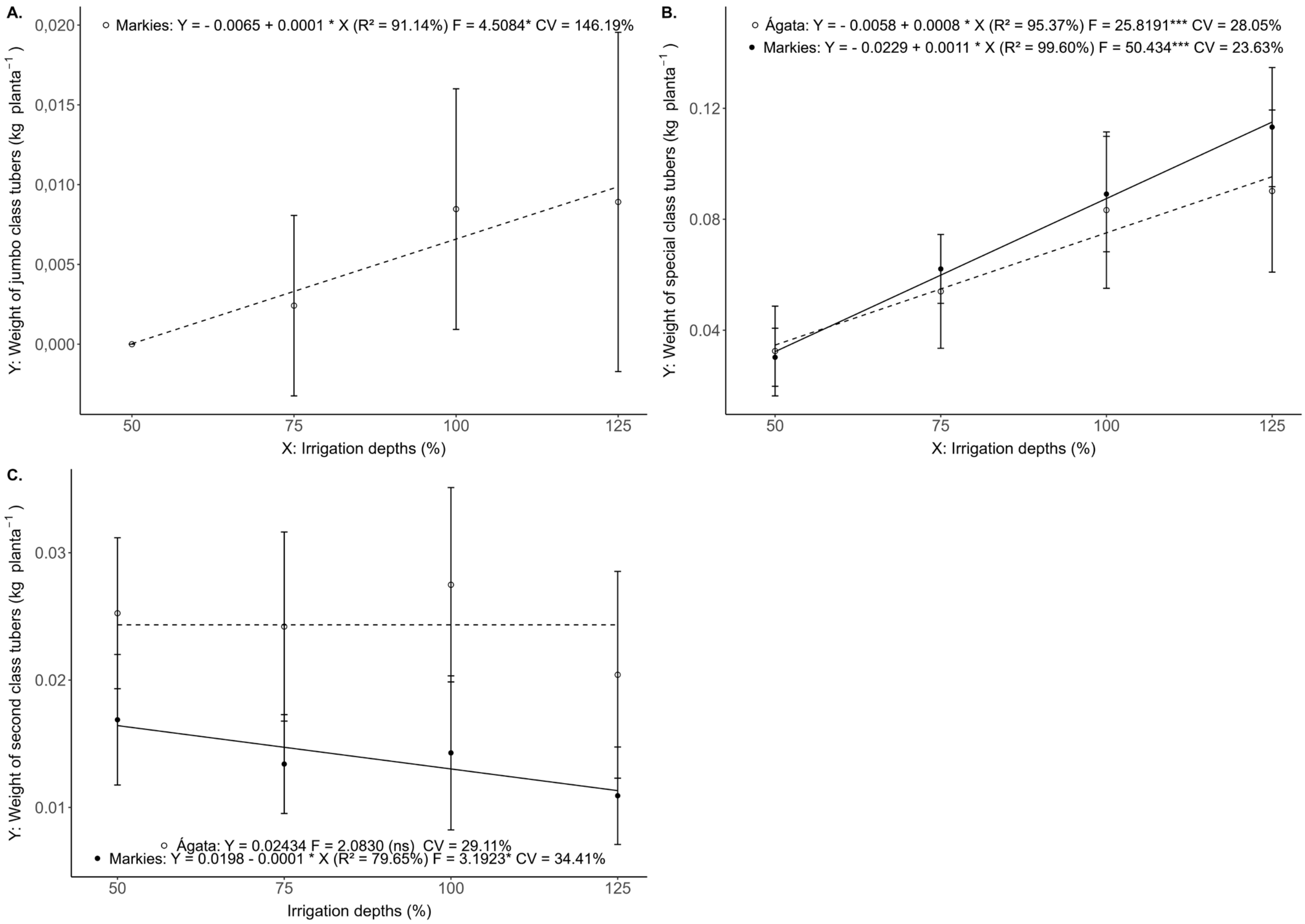

Figure 17: The average values for tuber weight of the jumbo class (a), large class (b), and small class (c) in potato plants of the Ágata and Markies cultivars as a function of different irrigation depths.

Conclusions

The seaweed extract-based fertilizer decreased the effects of water stress in the Markies cultivar. The highest irrigation depths were associated with an increase in the number and weight of tubers in the large classes for the Ágata and Markies cultivars.

Author Contributions

Conceptual idea: Castoldi, R; Nunes, G.F; Charlo, H.C.O; Methodology design: Castoldi, R; Data collect: Moreira, L.G; Diniz, N.M; Nunes, G.F; Data analysis and interpretation: Castoldi, R; Nunes, G.F; Prado, J.R; Charlo, H.C.O e Writing and editing: Castoldi, R; Nunes, G.F; Prado, J.R; Charlo, H.C.O; Jacinto, A.C.P.

References

Andrade, C. L. L. et al. (2018). Bioestimulantes derivados de Ascophyllum nodosum associados ao glyphosate nas características agronômicas da soja RR. *Revista Brasileira de Herbicidas*, *17*(3):e592.

Noroozlo, A. Y., Souri, M. K., & Delshad, M. (2019). Stimulation effects of foliar applied glycine and glutamine amino acids on lettuce growth. *Open Agriculture*, *4*(1):164-172.

Backes, C et al. (2017). Foliar application of seaweed extract on potato crops. *Revista de Agricultura Neotropical*, *4*(4):53-57.

Cabalceta, G., Saldias, M., & Alvarado, A. (2005). Absorción de nutrientes en el cultivar de papa MNF-80. *Agronomía Costarricense*, *29*(3):107-123.

Carvalho, J. B et al. (2018). Efficiency of borate fertilization in the development of eucalyptus seedlings. *Revista de Ciências Agrarias*, *61*:1-8.

De Albuquerque, P. E. P. (2010). *Irrigation management strategies: Calculation examples*. Minas Gerais: Sete Lagoas, (Technical Circular 136) 25p.

Faquin, V. (2002). *Diagnosis of plant nutritional status*. Lavras: UFLA/ FAEPE, (Texto Acadêmico) 77p.

Fernandes, A. M., & Soratto, R. P. (2012). *Mineral nutrition, liming and fertilization of potato plants*. Botucatu: FEPAF; Itapetininga: ABBA, 121p.

Franceschini, I. M. et al. (2010). *Algas:* Uma abordagem filogenética, taxonômica e ecológica. Porto Alegre: Artmed, 154p.

Friedrich, J. C. C. et al. (2020). Bio-stimulating: use in production of changes and results in commercial production. *Brazilian Journal of Development*, *6*(5):27392-27409.

Guidi, L., Lo Piccolo, E., & Landi, M. (2019). Chlorophyll fluorescence, photoinhibition and abiotic stress: does it make any difference the fact to be a C3 or C4 species? *Frontiers in Plant Science*, *10*:174.

International Potato Center - CIP. 2019. Lima. Potato Nutrition. Available in: <https://cipotato.org/crops/potato/>.

Jadoski, S. O., Suchoronczek, A., & Santos, J. (2017). Effect of water deficiency on vegetative development, production and physiological disorders in potato tubers. *Applied Research & Agrotechnology*, *10*(3):97-107.

Kissi, Y. A. et al. (2020). Influence of substrate composition on the morphophysiological performance of *Trema micrantha* (L.) seedlings Blume. *Challenges Magazine*, *7*(4):1-13.

Klein, C., & Agne, S. A. A. (2012). Phosphorus: From nutrient to pollutant. *Electronic Journal on Environmental Management, Education and Technology*, *8*(8):1713-1721.

Liu, C. et al. (2011). Effect of drought on pigments, osmotic adjustment and antioxidant enzymes in six woody plant species in karst habitats of southwestern China. *Environmental and Experimental Botany*, *71*:174-183.

Marcomini, G. R. (2020). Competitive advantages in potato production in Brazil and the United States. *Administração de Empresas em Revista*, *4*(22):246-270.

Martinazzo, E. G. et al. (2013). Photosynthetic activity in japanese plum under water deficit and flooding. *Ciência Rural*, *43*(1):35-41.

Mantovani, E. C. et al. (2013). Water use efficiency of two sweet potato cultivars in response to different irrigation depths. *Horticultura Brasileira*, *31*(4):602-606.

Monneveux, P. et al. (2013). Drought tolerance in potato (S. *tuberosum* L.). Can we learn from drought tolerance research in cereals? *Plant Science*, *205-206*:76-86.

Maxwell, K., & Johnson, G. (2000). Chlorophyll fluorescence a practical guide. *Journal of Experimental Botany*, *51*:659-668.

Oliveira, L. A. A. et al. (2011). Use of seaweed extract *(Ascophyllum nodosum*) in the production of yellow passion fruit seedlings. *Green Journal of Agroecology and Sustainable Development*, *6*(2):1-4.

Pedro, S. F. et at. (2022). Efeitos do fertilizante a base de extratos de algas marinhas no crescimento inicial do cafeeiro. *Research, Society and Development*, *11*(17):e79111738844.

Pieruschka, R. et al. (2012). Remote chlorophyll fluorescence measurements with the laser-induced fluorescence transient approach. *Methods in Molecular Biology*, *918*:51-59.

Pilon, C., Soratto, R. P., & Moreno, L. A. (2013). Soil and foliar application of soluble silicon to potato crops*(Solanum tuberosum* L.) under water deficiency. *Crop Science*, *53*:1605-1613.

Povero, G. et al. (2016). A systematic approach to discover and characterize natural plant biostimulants. *Frontiers in Plant Science*, *7*:435.

R Core Team (2023). *R foundation for statistical computing*. Vienna, Austria. Available in: <http://www.R-project.org/>.

Ribeiro, A. C., Guimarães, P. T. G., & Alvarez, V. V. H. (1999). *Recomendações para o uso de corretivos e fertilizantes em Minas Gerais*. 5th approach. Viçosa, MG: Soil Fertility Commission of the State of Minas Gerais, 359p.

Rodrigues, M. et al. (2022). Magnesium: A crop-enhancing macronutrient. *Agronomic Information*, *13*:1-24.

Singh, S. K., & Lal, S. S. (2012). Effect of potassium nutrition on potato yield, quality and nutrient use efficiency under varied levels of nitrogen application. *Potato Journal*, *39*:155-65.

Shukla, P. S. et al. (2019). *Ascophyllum nodosum*-based biostimulants: Sustainable applications in agriculture for the stimulation of plant growth, stress tolerance, and disease management. *Frontiers in Plant Science*, *10*(1):1-22.

Shukla, P. S. et al. (2017). Seaweed extract improves drought tolerance of soybean by regulating stress-response genes. *AOB Plants*, *10*(1):plx051.

Soratto, R. P., Fernandes, A. M., & Souza-Schlick, G. D. (2011). Extraction and export of nutrients in potato cultivars: II-micronutrients. *Revista Brasileira de Ciência do Solo*, *35*:2057-2071.

Souri, M. K., & Hatamian, M. (2019). Aminochelates in plant nutrition: A review. *Journal of Plant Nutrition*, *42*(1):67-78.

Souri, M. K., & Bakhtiarizade, M. (2019). Biostimulation effects of rosemary essential oil on growth and nutrient uptake of tomato seedlings. *Scientia Horticulture*, *243*:472-476.

Taiz, L. et al. (2017). *Fisiologia e desenvolvimento vegetal*. 6.ed. Porto Alegre: ArtMed. 888p.

Vayda, M. E. (1994). Environmental stress and its impact on potato yield. In Bradshaw, J. E. & Mackay, G. R. *Potato genetics*. Ed. Cabi, p. 239-261.

Zhou, L et al. (2019). Nutritional evaluation of different cultivars of potatoes (*Solanum tuberosum* L.) from China by gray relational analysis (GRA) and its application in potato steamed bread making. *Journal of Integrative Agriculture*, *18*(1):31-45.