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Agronomic Effects of Different Rock Powder Rates Associated with Irrigation Water Depths: Potential for Lettuce (*Lactuca sativa* L.) Production

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Abstract: Lettuce is among the 10 most valued vegetables for fresh consumption in Brazil. The use of rock powder in lettuce crops for soil acidity correction or fertilization is an option for reducing production costs. In this context, the objective of this study was to evaluate the effects of rock powder rates mica schist and irrigation water depths on the development and production characteristics of lettuce crops. The study was conducted in the experimental area of the State University of Goiás, using pelletized seeds of the lettuce cultivar Crespa Vanda. A randomized block experimental design with four replications was used, in a 4 × 4 factorial arrangement composed of four irrigation water depths: 50%, 75%, 100%, 125% of crop evapotranspiration (ETc), and four rock powder rates: 6, 8, 10, and 12 tons per hectare (t ha^{-1}), associated with mineral soil fertilizer application, totaling 16 treatments and 64 experimental plots. The variables evaluated were plant height, stem diameter, number of leaves, head diameter, total fresh weight, commercial fresh weight, leaf area index, useful leaf area, estimated yield, chlorophyll a, chlorophyll b, and water use efficiency. The data were subjected to regression analysis and principal component analysis. The variables studied exhibited predominantly low to medium coefficients of variation in all treatments, confirming the homogeneous conditions and precision of the study. The treatment with the highest rock powder rate (12 t ha^{-1}) provided the best results regarding agronomic effects for all lettuce crop variables evaluated. This rate provided better plant growth and development, resulting in improved response for production variables that are agronomically and economically relevant. The highest water use efficiency was found for the water depth of 50% ETc; however, the best lettuce production results were found for the irrigation water depth of 100% ETc. This water depth highlighted the strong correlation

of commercial and total fresh weights with commercial and total production, as they are production components of the crop.

Keywords: crisp lettuce; rock dust; agronomic and production variables; localized irrigation

1. Introduction

Lettuce (*Lactuca sativa* L.) is one of the most grown and consumed leafy vegetables throughout Brazil, despite the country's varied climate, with a high demand driven by consumption habits [1]. It is grown in all regions of Brazil, is one of the most-grown leafy vegetables in home gardens, and is the primary leaf vegetable consumed by the population, due to its low cost, flavor, and nutritional properties [2].

Lettuce is among the 10 most valued vegetables for fresh consumption in Brazil and, therefore, holds significant economic importance for the country [3]. It is a significant source of vitamin A and contains several other vitamins, including B1, B2, and C, as well as iron and calcium salts [4]. Lettuce crops are a great alternative economic activity for family farmers, as it is easy to produce and requires low maintenance. According to the Brazilian National Food Supply Company (Conab), Goiás is one of the largest lettuce-producing states in Brazil, supplying distribution centers with a production of 37,545 Mg, up to mid-December 2020.

Advances in agricultural production are essential in the search for alternatives that promote nutrient use efficiency, enabling increased food production using low-cost sources. In this context, the use of remineralizers such as rock powders has emerged as an alternative for growers [5]. According to Crusciol et al. [6], rock powder application helps mitigate problems caused by chemical fertilizer application and reduces production costs.

The use of rock powders for soil acidity correction or as a fertilizer is an alternative that reduces production costs and helps address the current dependency on imported inputs, such as magnesium, potassium, and phosphorus, without compromising crop yield [7]. Santos et al. [8] also reported that the use of basaltic powder rock, among others, restores soil mineral balance, resulting in the renewal of low-fertility or degraded soils, as they gradually add nutrients over time. The use of rock powder has several environmental benefits, including the reduced carbon footprint and the potential increase in carbon sequestration; therefore, crops using these remineralizers are characterized as low-carbon-emission systems [9]. In addition, rock powder is a source of nutrients to crops, it improves soil structure, and it increases soil water retention capacity, reducing nutrient leaching [10].

Modern agriculture seeks to develop crop systems that produce quality foods in large quantities, without harming the environment [11]. In this context, the use of inputs such as remineralizers has emerged as an alternative to the current production model, which focuses on reducing the dependency on traditional chemical fertilizers. This approach is important and should be promoted globally, as preservation of natural resources and sustainability are pivotal topics of discussion worldwide [12]. Crops grown in greenhouses are gradually increasing in Brazil; however, this system still has limitations regarding irrigation methods, as it is a closed environment [13]. The use of localized drip irrigation is one of the alternatives for these environments. Lettuce is a highly water- demanding crop (Villa e Vila et al., 2024); thus, its production requires adequate irrigation not only to meet the water demand, but also to increase nutrient absorption [14].

The drip irrigation system is among the localized methods used on large-scale crops; it presents easy maintenance and monitoring, improves water use, and minimizes waste,

making it the most efficient irrigation system [15]. Many lettuce crops are grown under conventional sprinkler irrigation systems; however, the search for more sustainable water use systems is increasing the use of localized drip irrigation, aiming to improve crop yield and quality [16].

The Brazilian state of Goiás presents favorable climate conditions for lettuce crops, allowing the sowing in any season of the year; however, the use of irrigation is sometimes necessary. Although some studies have evaluated and compared different products and systems for lettuce crops, current research on different irrigation water depths using drip irrigation associated with remineralizers such as rock powders and the application of foliar biofertilizers in lettuce does not exist; there is only the addition of the isolated products. Therefore, this area needs to be further researched, as the use of rock powder as fertilizer improves chemical, physical, and biological characteristics, enhancing environmental quality, and maintains nutrient balance for the crop. This approach contributes to reducing dependence on imported mineral fertilizers by utilizing a locally accessible resource in Brazil. In this context, the objective of this study was to evaluate the effects of rock powder rates and irrigation water depths on the development and production characteristics of lettuce crops.

2. Materials and Methods

2.1. Experimental Characterization

The experiment was conducted in a protected environment at the experimental area of the State University of Goiás (UEG), located in Santa Helena de Goiás, Goiás, Brazil (17°48′49″ S, 50°35′49″ W, at an altitude of 595 m). The region's climate is Aw (tropical savanna), according to the Köppen classification, characterized by a temperate climate with well-defined dry (May to September) and rainy (October to April) seasons. The mean annual temperature is 23 °C, with maximum temperatures reaching 39 °C. The lowest temperatures are observed from May to June, and the mean annual rainfall is 1300 mm [17]

The lettuce cultivar used in the study was pelletized Crespa Vanda Lettuce developed by Sakata seeds (Sakata Seed Sudamérica). The seedlings were produced in polyethylene tubes with a volume of 25 cm^3, to which commercial substrate was added. Sowing took place on 30 December 2021. The lettuce seedlings were transplanted into pots 23 days after sowing, on 22 January 2022. These polyethylene pots had a capacity of 15-L, which were filled with a soil classified as Typic Hapludox (Latossolo Vermelho Distrófico) [18] with a clay texture. The results of the soil's chemical and textural analyses are presented in Table 1.

Table 1. Results of the chemical and textural analyses of the soil (Typic Hapludox) used in the experiment.

pH	P (Meh)	K	S	Ca	Mg	Al	Ca + Mg	H + Al	T	CEC	OM
$CaCl_2$	mg dm^{-3}					$cmol_c$ dm^{-3}					g kg^{-1}
4.9	1.5	14.0	4.2	2.0	0.3	0.1	4.2	2.6	0.04	4.95	20.0
BS	**AS**	**Clay**	**Silt**	**Sand**		**Na**	**Zn**	**B**	**Cu**	**Fe**	**Mn**
%		g kg^{-1}				mg dm^{-3}					
47.39	4.10	570	120	310		1.3	0.3	0.08	1.8	17.0	30.8

CEC: cation exchange capacity; OM: organic matter; BS: base saturation; AS: aluminum saturation; pH: hydrogen potential; P (meh): phosphorus (Mehlich); K: potassium; S: sulfur; Ca: calcium; Mg: magnesium; Al: aluminum; Ca + Mg: calcium plus magnesium; H + Al: hydrogen plus aluminum; T: cation exchange capacity; B: boron; Cu: copper; Fe: iron; Mn: manganese; Zn: zinc; Na: sodium.

The composition of the rock powder of mica schist was determined through chemical and mineralogical analyses conducted at the Regional Center for Technological Development and Innovation (CRTI) of the UFG, Fern Campus, in Goiânia, Goiás, Brazil. Table 2 presents the quantitative mineralogical analysis of the rock dust sample. Table 3 shows

the minor elements analyzed in rock dust, while the major oxides present in rock dust are listed in Table 4. These analyses are essential as they aim to identify the mineralogical and chemical composition of the rock, focusing on the production of natural fertilizers, known as remineralizers. This type of rock dust has been widely used to complement conventional mineral fertilization.

Table 2. Result of quantitative mineralogical analysis of samples of the rock powder used in the experiment by Rietveld method.

Mineral	%
Microcline	0.56
Muscovite	22.33
Chlorite—Clinochlore	8.31
Biotite	13.61
Quartz	27.28
Oligoclase	27.09

Table 3. Result of chemical analysis of samples of the rock powder used in the experiment.

Minimum Detectable Limit (ppm)	Elements Analyzed	ppm
5	Sc	24
15	V	167
20	Cr	156
10	Co	19
10	Ni	64
15	Cu	59
20	Zn	117
5	Ga	25
10	Rb	86
20	Sr	153
15	Y	26
20	Zr	203
5	Nb	11
50	Ba	764
15	La	21
20	Ce	35
15	Pb	17

Table 4. Result of chemical analysis of oxides in the rock powder used in the experiment.

Oxides Analyzed	%
SiO_2	59.38
TiO_2	0.92
Al_2O_3	17.20
Fe_2O_3	8.19
MgO	4.15
CaO	1.61
Na_2O	2.37
K_2O	3.13
P_2O_5	0.24
LOI (%)	2.89
Sum (%)	100.07

LOI = loss on ignition.

A randomized block experimental design with four replications was used, in a 4 × 4 factorial arrangement composed of four irrigation water depths: 50%, 75%, 100%, and 125% of crop evapotranspiration (ETc), and four rock powder rates: 6, 8, 10, and 12 tons per hectare (t ha^{-1}), associated with mineral soil fertilizer application, totaling 16 treatments and 64 experimental plots. The rock dust doses were converted into grams per pot (g pot^{-1}), considering the soil mass based on the relationship between the pot volume and soil density. The corresponding doses, in the order mentioned above, were: 45.0 g pot^{-1}; 60.0 g pot^{-1}; 75.0 g pot^{-1}; and 90.0 g pot^{-1}.

Soil liming was performed to correct acidity and increase base saturation to 70%, as described by Filgueira [1], by adding 1.12 t ha^{-1} of calcitic limestone (Total Neutralizing Power of 100%). The limestone was applied together with the rock powder, focusing on standardizing the distribution.

Fertilizers were applied after seedling transplanting and as topdressing, calculated based on the soil (Table 1) and rock powder (Tables 2–4) chemical analyses, following recommendations for the crop. The fertilizer rates used were 30.0 kg ha^{-1} of N, 400 kg ha^{-1} of P_2O_5, 30.0 kg ha^{-1} of K_2O, and 1 kg ha^{-1} of B_2O_3 at the time of seedling transplanting. These doses were converted into grams per pot (g pot^{-1}), also considering the soil mass based on the relationship between the pot volume and soil density as previously described. The corresponding doses were: 0.22 g pot^{-1} of N; 3.0 g pot^{-1} of P_2O_5; 0.23 g pot^{-1} of K_2O; and 7.5 mg pot^{-1} of B_2O_5. Additionally, 90 kg ha^{-1} of N (0.68 g pot^{-1} of N) and 60 kg ha^{-1} of K_2O (0.46 g pot^{-1} of K_2O) were applied, as topdressing, split into two applications, at 15 and 30 days after transplanting the seedlings into the pots. The amounts of nutrients needed for the lettuce crop development and application timing were based on recommendations described by Rezende [19].

The different rock powder rates were quantified based on the recommendation for each nutrient, and the remaining nutrient requirements were supplemented with conventional mineral soil fertilizers (urea, simple superphosphate, potassium chloride, and boron), ensuring the same quantity of each nutrient for all treatments.

Each plot consisted of one pot; the pots were spaced 0.30 m between plants and 0.30 m between rows, following the recommendation for the crop. The irrigation water depths were applied through a drip system with one emitter per pot, with one line for each row of pots. The emitters had nominal flow of 1.6 L h^{-1}, operation pressure of 8 mwc (meters of water column). Tests were conducted to determine the water application efficiency and distribution uniformity, for an efficient water application [20].

The mean Christiansen uniformity coefficient (CUC), Christiansen distribution uniformity coefficient (CUD), and application efficiency (AE) evaluated are shown in Table 5. The estimated values demonstrated that the system was excellent in terms of water supply, based on to the methodology of Merriam and Keller [21].

Table 5. Christiansen uniformity coefficient (CUC), Christiansen distribution uniformity coefficient (CUD) and application efficiency (AE), and classification of the irrigation system used in the experiment.

System	CUC (%)	CUD (%)	AE (%)	Classification
Drip	100.0	97.98	88.19	Excellent

A mini-Class A tank was used for irrigation management, installed inside the greenhouse, and calibrated as described by Santos et al. [22], based on Class A tank standards. The evaporation in the Class A tank was determined through daily readings of evaporation in the mini tank, with corrections as described by Santos et al. [22], using Equation (1):

$$ECA = (1.4035 \times EMT) + 1.2456 \quad (1)$$

where,

ECA = Evaporation in the Class A tank (mm day^{-1});
EMT = Evaporation in the mini tank (mm day^{-1}).

The daily result obtained from Equation (1) was used to calculate the reference evaporation (ET_o), using Equation (2), as described by Allen et al. [23] according to the Equation (3).

$$ET_o = ECA \times K_t \quad (2)$$

where,

ET_o = Reference evapotranspiration (mm day^{-1});
K_t = Coefficient of the tank (dimensionless);
ECA = Evaporation in the Class A tank (mm day^{-1}).

The crop evapotranspiration (ET_c) was obtained using the FAO's standard method [23], using Equation (3):

$$ET_c = ET_o \times K_c \quad (3)$$

where,

ET_c = Crop evapotranspiration (mm day^{-1});
ET_o = Reference evapotranspiration (mm day^{-1});
K_c = Crop coefficient (dimensionless).

The crop coefficient (K_c) was determined using a variation of 0.5 to 1.05, depending on the lettuce developmental stages, using 0.5 for the first stage (0 to 25 days); 0.7 for the second stage (26 to 35 days); 1.05 for the third stage (36 to 44 days); and 1.0 for the fourth stage (44 to 60 days) [23,24].

The ET_c in Equation (3) was calculated considering 100% of the water required for the crop. This value was multiplied by 0.5, 0.75, and 1.25 for the other treatments, corresponding to 50%, 75%, and 125% ETc, respectively, it is worth mentioning that irrigation in all treatments was applied daily based on ETc on a daily scale.

A fixed watering shift of 1 day was used for the irrigation management during the crop cycle [23,25]. The irrigation water depths were determined using the total irrigation water depth required, calculated with Equation (4):

$$TWD = \frac{ET_c \times WS}{E_a} \quad (4)$$

where,

TWD = Total irrigation water depth needed (mm);
ET_c = Crop evapotranspiration (mm day^{-1});
WS = Watering shift (1 day);
E_a = Irrigation efficiency (dimensionless).

The irrigation time was calculated using Equation (5) [23,25]:

$$Ti = \frac{TWD \times E1 \times Eg}{q} \quad (5)$$

where,

Ti = Irrigation time (min);
TWD = Total irrigation water depth needed (mm);
E1 = Spacing between lateral rows (m);
Eg = Spacing between the drippers (m);
q = dripper flow (L h^{-1}).

Weeds were controlled through manual weeding. Ants were controlled after their incidence was detected in the greenhouse by applying the insecticide fipronil (Regente 800; 800 g kg^{-1}) at the rate of 1 g L^{-1}.

The lettuce plants were manually harvested in the morning and afternoon periods at 54 days after sowing, when they reached maximum vigor, which typically occurs between 45 and 60 days [19].

2.2. Temperatures Inside the Protected Environment

Maximum, minimum, and mean air temperatures (°C) inside the protected environment were measured using a digital thermohygrometer with a measurement range of −10 to 60 °C, a resolution of 0.1 °C, and an accuracy of ±1 °C. Temperatures were measured at a height of 1.0 m above ground level, in the mornings, at the time the drip irrigation system was activated.

2.3. Agronomic and Production Characteristics of the Lettuce Crops

Lettuce plants were harvested 54 days after sowing. The crop agronomic and production characteristics evaluated included: plant height, measured from the ground to the top of the plant (cm); stem diameter, measured at a height of approximately 3 cm from the stem base, using a digital caliper (mm); number of leaves, determined by counting the leaves of each plant in each experimental plot; leaf area index, calculated by multiplying the rib main length by the maximum leaf width and applying a correction factor of 0.75, as used for lettuce [26]; useful leaf area, determined by multiplying the main rib length by the maximum leaf width [26]; head diameter, measured as the length between opposite leaves using a ruler (cm); total fresh weight, measured by weighing the entire plant, including all leaves, using an analytical balance (g $plant^{-1}$); commercial fresh weight, measured by weighing only useful leaves using an analytical balance, after removing external leaves (burned or yellowish) that are not suitable for consumption (g $plant^{-1}$); yield, estimated by the weight of all plants, converted into kilograms per hectare based on the planting spacing used (kg ha^{-1}); chlorophyll a and chlorophyll b, measured using a clorofiLOG device; and water use efficiency, determined by correlating the estimated yield (kg ha^{-1}) with the total quantity of water applied (mm) over the crop cycle for each treatment.

2.4. Statistical Analyses

The data obtained were subjected to analysis of variance (ANOVA) using the F-test at 1% and 5% probability level to assess significant effects. The data related to the different irrigation water depths and rock powder rates applied to the lettuce crops were then subjected to regression analysis, using the RStudio 4.03 software [27].

The data were subjected to principal component analysis (PCA). A covariance matrix was developed to extract eigenvalues, which were used to generate eigenvectors based on the principal components. The Kaiser criterion was applied to identify correlated variables, considering eigenvalues above 1, which indicate components with sufficient information contained in the original data [28]. The statistical analyses were conducted using the RStudio 4.03 software [27].

3. Results and Discussion

3.1. Temperatures and Crop Evapotranspiration Inside the Protected Environment

The results of maximum, minimum, and mean air temperatures (°C) and crop evapotranspiration (ETc; mm day^{-1}) inside the protected environment are shown in Figure 1. The ETc during the study period ranged from 2.07 to 9.67 mm day^{-1}. The mean temperature inside the greenhouse ranged from 34.9 to 36.1 °C, with minimum temperatures ranging

from 17.3 to 39.1 °C and maximum temperatures ranging from 23.1 to 49.4 °C (Figure 1). Michelon et al. [29] evaluated strategies for improving water use efficiency in lettuce crops and reported mean maximum temperatures of 35.6 °C in one of the experiments, a value close to that found in the present study. The temperatures during the experiment were high because the protected environment was covered by a diffuser plastic film, and the crop cycle coincided with the summer season. Therefore, the mean temperatures were outside the recommended range of 15.5 to 18.3 °C and the tolerance range for maximum temperatures of 26.6 a 29.4 °C for crops in open fields [30].

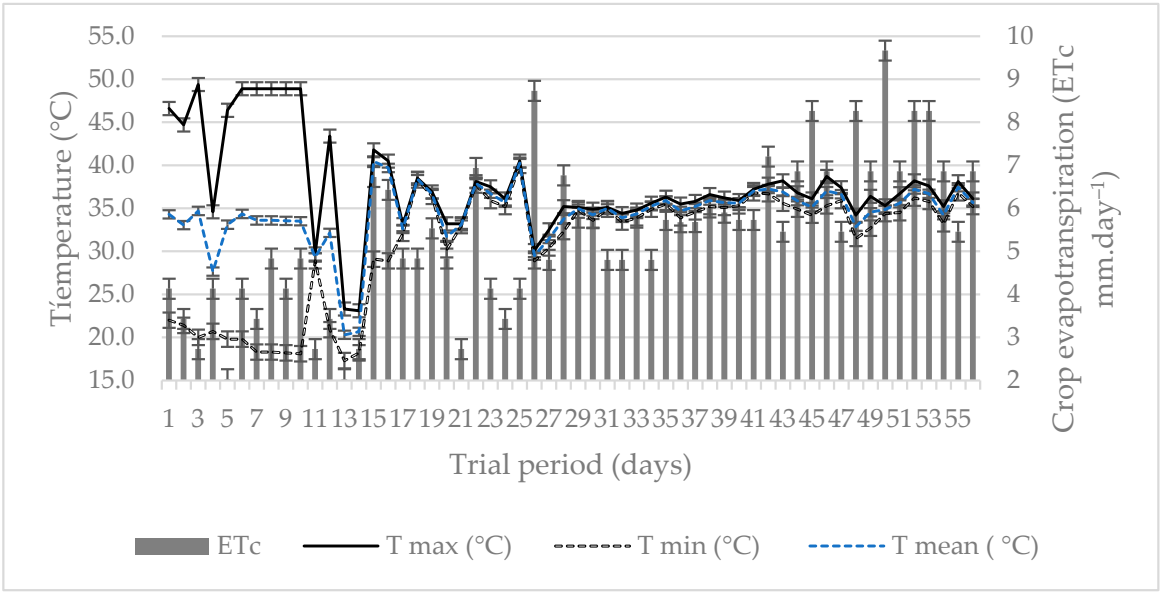

Figure 1. Temperature and crop evapotranspiration inside the protected environment during the lettuce crop cycle.

However, the cultivar Vanda adapts well to varied conditions of temperature and relative humidity, exhibiting high hardiness and productivity even under tropical climates. Thus, the micrometeorological components had no negative effect on the growth, development, or yield of the lettuce cultivar studied, which demonstrated satisfactory productivity under the evaluated conditions. These results are consistent with those of Fernandes et al. [31], who investigated agrometeorological conditions for lettuce cultivars and found no direct relationship between the development and yield of the cultivar 'Bruna' and agrometeorological variables. These researchers also concluded that, although climatic elements are crucial for plant growth and development, they do not directly affect lettuce cultivars or phytotechnical characteristics under protected environment conditions.

3.2. Analysis of Variance and Regression

The analysis of variance (ANOVA) (Table 6) revealed a significant effect ($p < 0.01$) of the irrigation water depths on all agronomic and production characteristics studied. However, the effect of the rock powder rates and the interaction between the rock powder rates and irrigation water depths were not significant.

The lack of significance of rock powder rates and their interaction with irrigation water depths on the evaluated characteristics was likely due to the short cycle of the lettuce crop and the slow remineralization of rock powder, which requires a longer time in the soil to release minerals. However, the use of rock powder is viable, as it supplied the nutrients required for crop development. Lajús et al. [5] also highlighted the slow nutrient

release of rock powder compared to more soluble chemical fertilizers; however, the slow remineralization is compensated by the longer nutrient availability period in the soils.

Table 6. Analysis of variance (ANOVA) based on the F-statistic for the effects of irrigation water depths (IWD), rock powder rates (RPR), and their interaction on the agronomic and production characteristics of lettuce crops.

Source of Variation	PH	SD	NL	HD	TFW	CFW
IWD	20.85 *	13.06 *	22.76 *	8.97 *	13.84 *	11.81 *
RPR	2.15 ^{ns}	0.17 ^{ns}	2.749 ^{ns}	0.81 ^{ns}	2.25 ^{ns}	2.47 ^{ns}
IWD × RPR	1.06 ^{ns}	0.82 ^{ns}	0.89 ^{ns}	1.25 ^{ns}	0.81 ^{ns}	0.50 ^{ns}
Block	1.39	0.44	1.46	1.59	1.16	0.28
Error	-	-	-	-	-	-
Total	-	-	-	-	-	-
CV	8.97	12.41	8.25	8.53	18.33	20.22
Source of variation	LAI	ULA	EY	CLa	CLb	WUE
IWD	16.34 *	16.34 *	13.84 *	252.91 *	156.66 *	21.90 *
RPR	1.31 ^{ns}	1.31 ^{ns}	2.25 ^{ns}	12.90 *	13.14 *	1.80 ^{ns}
IWD × RPR	0.64 ^{ns}	0.63 ^{ns}	0.81 ^{ns}	3.33 ^{ns}	3.32 ^{ns}	0.54 ^{ns}
Block	0.01	0.01	1.16	3.31	3.67	1.47
Error	-		-	-	-	-
Total	-		-	-	-	-
CV	12.67	12.67	18.33	3.68	7.57	20.71

PH = plant height (cm); SD = stem diameter (mm); NL = number of leaves; HD = head diameter (cm); TFW = total fresh weight (g plant^{-1}); CFW = commercial fresh weight (g plant^{-1}); LAI = leaf area index; ULA = useful leaf area; EY = estimated yield (kg ha^{-1}); CLa = chlorophyll a; CLb = chlorophyll b; WUE = water use efficiency (kg ha^{-1} mm^{-1}). ^{ns} and * = not significant and significant at 1% by the F-test.

Similar results were reported by Rezende et al. [19], who then evaluated the use of rock powder as a soil fertilizer for lettuce plants and found that the basalt powder rates tested, either alone of or combined with cattle manure, resulted in no significant variation. In addition, Dalcin et al. [32] evaluated the effect of adding rock powder to a Typic Hapludult on the growth of lettuce plants of the cultivar Vanda and found no increase in shoot fresh and dry weights, plant height, number of leaves, or stem diameter over a period of 42 days.

However, Santana et al. [33] evaluated the responses of lettuce cultivars to irrigation water depths and nitrogen rates and found that the different water depths had a significant effect on number of leaves and plant height for the cultivar Americana Grandes Lagos 659. They also found a significant effect of irrigation water depths for plant height, shoot weight, number of leaves, and root fresh weight for the cultivar Crespa Mônica. Moreover, the water depths of 100% and 125% ETc combined with the urea rate of 125 kg ha^{-1} resulted in better development and growth of lettuce plants.

Overall, the coefficients of variation (CV) of the variables (Table 6) based on the criteria of Warrick and Nielsen [34] were considered low (CV < 12%) to medium (CV = 12–24%). This indicates lower variability and homogeneity of abiotic factors in the protected environment.

The regression equations for each evaluated characteristic and their respective coefficients of determination are shown in Table 7. The number of leaves increased linearly with the water depth, with means ranging from 16.5 to 20.5 between the water depths of 50% and 125% ETc. Magalhães et al. [35] evaluated the lettuce cultivars Rapids, Mônica, and Simpson using irrigation levels of 50% to 125% ETc and found an increasing linear effect for the number of leaves as a function of increasing irrigation water depth, which varied from 8.21 to 14.63 leaves per plant. Higher results were obtained in the present study.

Table 7. Regression equations, coefficients of determination (R^2), and overall mean and standard deviation (SD) for variables of lettuce crops as a function of irrigation water depths (% ETc).

Variables	Regression Equations	R^2	Mean ± SD
PH (cm)	Y = 0.0588 * X + 14.442	0.8948	19.59 ± 2.50
SD (mm)	Y = 0.351 * X + 7.781	0.8977	10.85 ± 1.64
NL	Y = 0.0541 * X + 13.462	0.9522	18.20 ± 2.19
HD (cm)	Y = 0.0515 *X + 24.268	0.8185	28.78 ± 2.94
TFW (g)	Y = −0.00138 * X^2 + 0.294X + 64.70	0.9901	102.12 ± 24.06
CFW (g)	Y = −0.00147 * X^2 + 0.4721X + 66.28	0.9931	92.85 ± 12.84
LAI	Y = 0.7597 * X + 137.29	0.8827	203.77 ± 33.13
ULA	Y = = 1.0176 * X + 182.66	0.8908	271.69 ± 44.18
EY (kg ha^{-1})	Y = −0.15286 * X^2 + 32.743X + 7180.08	0.9901	11,334.88 ± 267.19
CLa	Y = 0.1072 * X + 14.77	0.9608	24.15 ± 3.32
CLb	Y = 0.0465 * X + 2.398	0.9616	6.47 ± 1.51
WUE (kg ha^{-1} mm^{-1})	Y = −0.283 * X + 64.67	0.8930	39.90 ± 3.41

PH = plant height; SD = stem diameter; NL = number of leaves; HD = head diameter; TFW = total fresh weight; CFW = commercial fresh weight; LAI = leaf area index; ULA = useful leaf area; EY = estimated yield; CLa = chlorophyll a; CLb = chlorophyll b; WUE = water use efficiency.

The lettuce plant height, stem diameter, and head diameter also exhibited linear responses as a function of irrigation water depths (Table 7), with mean plant height varying from 17.97 to 22.33 cm, with stem diameters from 9.41 to 11.93 mm, and head diameter from 27.15 to 30.41 cm. The lowest values of these characteristics were observed for the water depth of 50% ETc, and the highest for 125% ETc; these results are consistent with those obtained by Bozkurt et al. [36]. Many plant species have shallow root systems and are sensitive to moderate water stress; in the case of lettuce, the commercial part of the plant is the leaf, thus, maintaining adequate growth requires proper water application to ensure satisfactory yield [36]. Silva et al. [37] evaluated plant height of irrigated 'Vanda' lettuce crops and found a linear response to irrigation water depths of 50% to 125% ETc, with a 12.55% increase in plant height. The head diameter results found in the present study were similar to those reported by Schumacher et al. [38], who evaluated a conventional system and found mean head diameter of 34.21 cm $plant^{-1}$.

Leaf area index and useful leaf area increased linearly with the water depth, with the lowest values observed for the water depths of 50% ETc and the highest for the 125% ETc (Table 7 and Figure 2). According to Hou et al. [39], increases in the leaf area of plants subjected to irrigation with higher water rates are connected to the greater hydration of leaf tissues. A study reported that higher irrigation water depths result in significant increases in leaf area [40]. Additionally, Alvim et al. [41] reported that the leaf area index is one of the most important factors for characterizing plant growth because the leaves are the primary photosynthetic structures directly linked to yield increases, as evidenced in the present study.

The means obtained for the production characteristics (total fresh weight, commercial fresh weight, and estimated yield) fit to a quadratic regression equation ($p < 0.01$) (Table 7). The water depth of 106.52% ETc resulted in the maximum estimated fresh weight (113.07 g $plant^{-1}$); the maximum estimated commercial fresh weight (99.29 g $plant^{-1}$) was observed at the water depth of 102.86% ETc; and the maximum estimated yield (12,440.88 kg ha^{-1}) was achieved with the water depth of 107.11% ETc. These results are consistent with those obtained by Cahn et al. [42], who evaluated the water requirements, nitrogen use, and yield of lettuce crops under ETc-based irrigation and found higher fresh and dry biomass yields in treatments with 100% ETc, with no significant difference compared to treatments with 150% ETc. Similar results were found by Abd-Elrahman et al. [43], who evaluated the effect of irrigation water depths associated with fertilizer application

on lettuce yield. According to Michelon et al. [29], irrigation affects lettuce total and commercial fresh weights, reaching a difference of 29% between water depths of 25% and 100% ETc, respectively, directly affecting the crop yield.

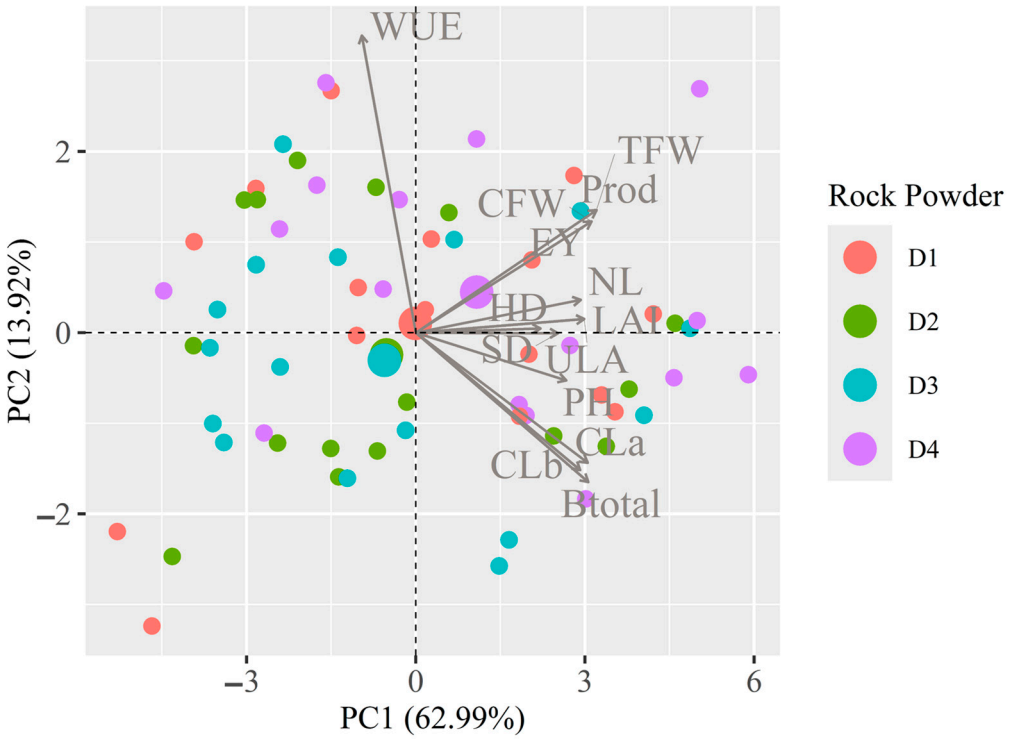

Figure 2. Principal component analysis (PCA) of agronomic and production characteristics of lettuce crops subjected to rock powder rates of 6 (D1), 8 (D2), 10 (D3), and 12 (D4) t ha^{-1}. Note: DF = degrees of freedom; PH = plant height (cm); SD = stem diameter (mm); NL = number of leaves; HD = head diameter (cm); TFW = total fresh weight (g plant^{-1}); CFW = commercial fresh weight (g plant^{-1}); LAI = leaf area index; ULA = useful leaf area; EY = estimated yield (kg ha^{-1}); CLa = chlorophyll a; CLb = chlorophyll b; WUE = water use efficiency (kg ha^{-1} mm^{-1}).

Chlorophyll a and chlorophyll b contents increased as the water depth was increased (Table 7 and Figure 2). Shin et al. [44] monitored changes in chlorophyll contents, growth parameters, and phytochemical parameters of lettuce seedling leaves under water stress and found that chlorophyll contents decreased in seedlings stressed by water deficit.

Water use efficiency (WUE) exhibited a linear decreasing trend (Table 7 and Figure 2), with the highest WUE at the water depth of 50% ETc and the lowest in the water depth of 125% ETc. Magalhães et al. [35] evaluated four irrigation water depths (50%, 75%, 100%, and 125% ETc) applied through a drip system for three lettuce cultivars (Simpson, Rapids, and Mônica) and found that increases in irrigation water depths decreased the water use efficiency and increased shoot fresh weight. These results are similar to those found in the present study and provide evidence that more efficient water use does not always result in higher crop yields [43].

The principal component analysis (PCA) of agronomic and production characteristics of the lettuce crops (Figure 2) showed that the eigenvalues of principal components 1 (PC1) and 2 (PC2) were above 1, based on the criterion of Kaiser [28]. This indicates the high significance of these components in explaining the variation among the variables. The total variance explained by PC1 and PC2 were 62.99% and 13.92%, respectively, significantly explaining correlations between the variables (Figure 2). These results are similar to those obtained by Silva et al. [45], who conducted a PCA on morphometric, production, and quality variables of cherry tomato crops under different irrigation water depths and found

eigenvalues above 1 (PC1 = 4.06 and PC2 = 1.64), meeting the significance criteria for the variables. Machado et al. [46] evaluated the agronomic performance of lettuce cultivars grown in a greenhouse and observed eigenvalues above 1.0 (PC1 = 3.89 and PC2 = 1.21).

Figure 2 illustrates that all agronomic and production characteristics of lettuce crops exhibited the best responses to the rock powder application rate of 12 t ha^{-1}, except WUE. Therefore, applying 12 t ha^{-1} of rock powder enhanced plant height, number of leaves, stem diameter, head diameter, total fresh weight, commercial fresh weight, leaf area index, useful leaf area, estimated yield, and chlorophyll a and chlorophyll b contents. Rock dust has shown potential to improve soil fertility and plant nutrition, as its nutrients are gradually released and remain available in the soil for a longer period. This slow release allows for continuous crop nutrition, resulting in balanced and healthy plant growth.

The estimated yield exhibited a strong correlation with total fresh weight and commercial fresh weight, as expected, since these production variables are interconnected. Similarly, chlorophyll a and chlorophyll b exhibited a strong correlation and higher contents with the application of 12 t ha^{-1} of rock powder, as increases in chlorophyll in lettuce leaves due to remineralizer application is associated with high silicon concentration availability in the soil, mainly when using high rates [47]. Similarly, Maldaner et al. [48] evaluated the effect of basalt powder rates on lettuce crops and found that the highest rate increased the contents of these pigments.

The findings of this study corroborate those of Augusto et al. [49], who evaluated organic lettuce production using different basaltic rock powder rates, organic compost, and microorganisms and found that the use of rock powder increased the number of leaves, commercial dry weight, root fresh weight, head commercial diameter, and stem length of Americana lettuce. Groth et al. [50] also found similar responses when analyzing the effects of applying three basalt powder sources on the performance of lettuce plants.

Rock powder slowly releases nutrients into the soil solution in ideal forms and quantities for plant absorption [51,52]. Thus, the highest rate (12 t ha^{-1}) led to the release of a higher quantity of nutrients in a short period (Figure 2), as this remineralizer promotes an increase in soil cation exchange capacity [52], resulting in improved responses in lettuce plants. This rate (12 t ha^{-1}) likely provided a chemical balance in the soil, resulting in improved plant growth, development, and vigor, increasing the plant's capacity to absorb and retain CO_2. Li et al. [53] and Arnott et al. [51] reported that the use of rock powder is a sustainable technique that increases CO_2 retention, provides nutrients to the soil and plants, and acts as a soil pH regulator.

Principal component analysis (PCA) was also conducted for agronomic and production characteristics of lettuce crops subjected to irrigation water depths of 50%, 75%, 100%, and 125% ETc, as illustrated in Figure 3. The total cumulative variance explained by PC1 and PC2 was 76.91%; these results are significant in explaining the correlations observed between the studied characteristics, according to the criterion of Kaiser [28].

The water depth of 50% ETc resulted in a higher WUE, which decreased as the applied water depth increased (Figure 3 and Table 7). This occurs because when higher irrigation levels are used, efficiency tends to decrease, reaching its maximum with lower irrigation levels. This is because Water Use Efficiency (WUE) is determined by the ratio between crop yield and the total amount of water supplied to the crop throughout the production cycle. These results corroborate those of Abd-Elrahman et al. [43], who studied irrigation water depths associated with fertilizer application in lettuce crops. Furthermore, Michelon et al. [29] evaluated improvements in WUE in irrigated lettuce and observed that lower irrigation water depths resulted in higher WUE, as the irrigation of 50% ETc was more efficient. Therefore, the WUE observed in the present study was inversely proportional to increases in irrigation water depth and consistent with studies conducted in

different locations, which reported inverse correlations between WUE and irrigation water depths [54,55].

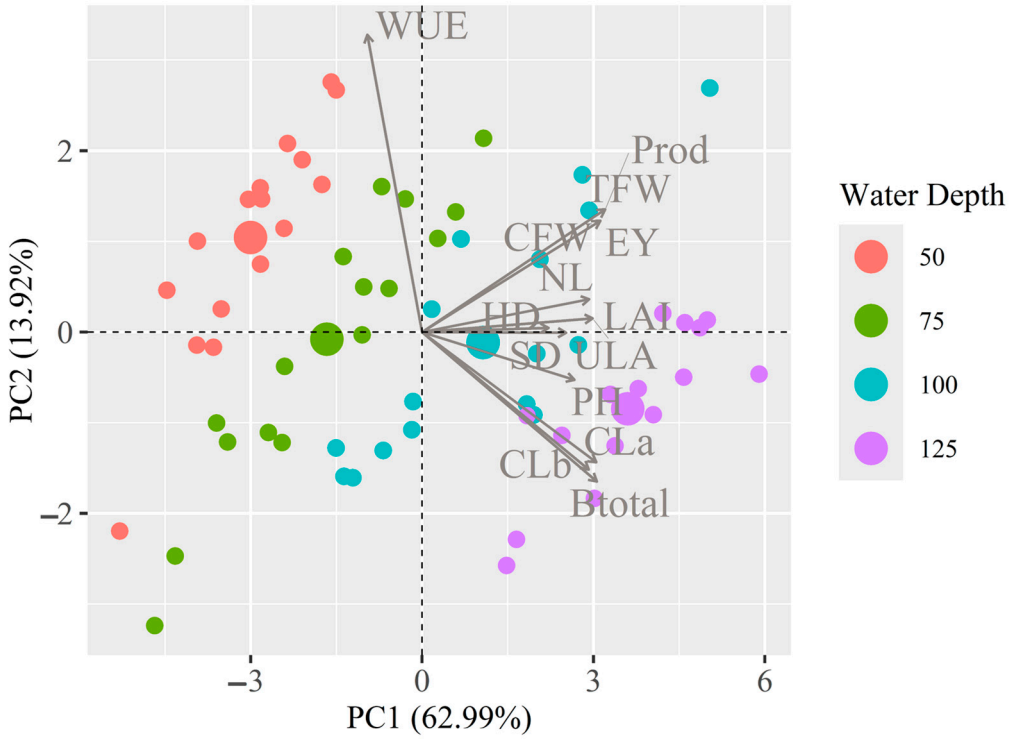

Figure 3. Principal component analysis (PCA) of agronomic and production characteristics of lettuce crops subjected to irrigation water depths of 50%, 75%, 100%, and 125% ETc. Note: DF = degrees of freedom; PH = plant height (cm); SD = stem diameter (mm); NL = number of leaves; HD = head diameter (cm); TFW = total fresh weight (g plant^{-1}); CFW = commercial fresh weight (g plant^{-1}); LAI = leaf area index; ULA = useful leaf area; EY = estimated yield (kg ha^{-1}); CLa = chlorophyll a; CLb = chlorophyll b; WUE = water use efficiency (kg ha^{-1} mm^{-1}).

The principal component analysis (Figure 3) showed that total fresh weight, commercial fresh weight, and estimated yield were strongly correlated with the irrigation water depth of 100% ETc. The other agronomic characteristics (plant height, stem diameter, head diameter, leaf area index, useful leaf area, chlorophyll a, and chlorophyll b) were strongly correlated with the irrigation water depth of 125% ETc (Table 7). Cahn et al. [42] obtained similar results, with irrigation at 100% ETc providing the most suitable environment for producing commercially viable yields. An experiment with Americana lettuce subjected to different irrigation water depths conducted by Lima Junior et al. [56] revealed that the maximum estimated yield was obtained at an irrigation water depth of 98%. In a similar study, Lima Junior et al. [57] observed the highest yield for the lettuce cultivar Raider Plus when applying a water depth of 101% ETc; these results are close to those found in the present study.

4. Conclusions

The treatment with the highest rock powder rate (12 t ha^{-1}) led to the best agronomic results across all studied characteristics of lettuce crops. This rate enhanced growth and development of lettuce plants, ultimately improving production variables, which are the most agronomically and economically relevant.

The use of rock powder in agriculture is a novel, sustainable, and promising approach with high potential to improve practices in important crops, including leafy vegetables cultivated worldwide. However, further studies are needed to optimize its application.

The water depth of 50% ETc led to the highest water use efficiency (WUE); however, maximum WUE does not always correspond to the highest plant quality and yield.

The water depth of 125% ETc increased plant height, stem diameter, head diameter, leaf area index, useful leaf area, and chlorophyll a and chlorophyll b contents. However, to highest lettuce yields were achieved at an irrigation water depth close to 100% ETc. This water depth showed a strong correlation between commercial and total fresh weights with commercial and with total production, as these are key crop yield components.

Irrigation significantly influences the agronomic and productive characteristics of lettuce crops, making it a crucial factor in commercial productions.

Therefore, under the conditions in which the present experiment was conducted, the application of 100% of the crop evapotranspiration (ETc) is recommended to achieve higher productivity and commercial-scale quality. This recommendation is based on the fact that the most efficient water use was neither the most productive nor the one that promoted the best agronomic performance for lettuce cultivation.

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