agriculture

Article

Effects of Fertilization Types and Base Saturation on the Growth and Water Productivity in *Panicum maximum* cv. BRS Zuri

Niclene Ponce Rodrigues de Oliveira [1], Edna Maria Bonfim-Silva [1,*], Tonny José Araújo da Silva [1], Patrícia Ferreira da Silva [1], Rosana Andréia da Silva Rocha [2], Luana Aparecida Menegaz Meneghetti [2], Alisson Silva Costa Custódio [2], Salomão Lima Guimarães [1], Thiago Franco Duarte [1] and Marcio Koetz [1]

[1] Department of Agricultural Engineering, Institute of Agricultural and Technological Sciences—ICAT, Federal University of Rondonópolis, Av. dos Estudantes, 5055, Cidade Universitária, Bloco C, Rondonópolis 78736-900, MT, Brazil; niclene_ponce@hotmail.com (N.P.R.d.O.); tonnyjasilva@gmail.com (T.J.A.d.S.); patrycyafs@yahoo.com.br (P.F.d.S.); salomao@ufr.edu.br (S.L.G.); thiago.duarte@ufr.edu.br (T.F.D.); marcio.koetz@ufr.edu.br (M.K.)

[2] Postgraduate Program in Tropical Agriculture, Faculty of Agronomy and Animal Science—FAAZ, Federal University of Mato Grosso, Av. Fernando Corrêa da Costa, 2367, Boa Esperança, Cuiabá 78060-900, MT, Brazil; rocharosana890@gmail.com (R.A.d.S.R.); luana_m.meneghetti@hotmail.com (L.A.M.M.); alissonsilvadk@gmail.com (A.S.C.C.)

* Correspondence: embonfim@hotmail.com or edna.bonfim@ufr.edu.br

Abstract: Fertilization management is essential for forage production. However, excessive use of synthetic fertilizers causes environmental imbalances. An alternative to reduce these effects is to seek alternative fertilizers, such as wood ash produced from agro-industrial waste, when integrated with appropriate base saturation management. This study aims to compare the effects of fertilization with wood ash (WA), organomineral (OM), and mineral (M) fertilizers associated with different levels of base saturation on the growth and water productivity of *Panicum maximum* cv. BRS Zuri. The experiment was conducted in a greenhouse, using a randomized block design in a 3 × 3 factorial arrangement. The treatments consisted of three types of fertilization (WA, OM and M) and three levels of base saturation (0, 25%, and 50%). Leaf area, chlorophyll index, shoot dry mass and root dry mass, water consumption, and water productivity of Zuri grass were evaluated. The results showed significant increases in leaf area, with values of up to 4564.5 $cm^2.pot^{-1}$ and a chlorophyll index of up to 36.2 units. In addition, the dry mass of the aerial part reached up to 46.7 $g.pot^{-1}$, and the dry mass of the roots reached 21.7 $g.pot^{-1}$ with the use of OM fertilizers. These values represent an increase of between 43.1% and 69.6% compared to the values of conventional fertilizers. In addition, water productivity reached 4.9 $g.L^{-1}$ with WA-based fertilizers, an increase of around 39% compared to the values of mineral fertilizers.

Keywords: wood ash; organomineral; mineral (NPK); agricultural sustainability

check for updates

Citation: de Oliveira, N.P.R.; Bonfim-Silva, E.M.; da Silva, T.J.A.; da Silva, P.F.; da Silva Rocha, R.A.; Meneghetti, L.A.M.; Custódio, A.S.C.; Guimarães, S.L.; Duarte, T.F.; Koetz, M. Effects of Fertilization Types and Base Saturation on the Growth and Water Productivity in *Panicum maximum* cv. BRS Zuri. *Agriculture* **2023**, *13*, 1872. https://doi.org/10.3390/agriculture13101872

Academic Editor: José Manuel Rato-Nunes

Received: 11 August 2023
Revised: 20 September 2023
Accepted: 21 September 2023
Published: 25 September 2023

1. Introduction

Proper nutrient supply to plants through fertilization combined with water management is crucial for increasing the growth and productivity of crops, ensuring agricultural sustainability, and this holds true for forage species as well [1]. In this context, Zuri grass (*Panicum maximum* cv. BRS Zuri) has drawn interest due to its potential as a forage grass considering its adaptability to different environmental conditions [2]. However, it is important to explore alternative fertilization practices, as well as levels of base saturation and water management strategies, aimed at optimizing the productivity of this forage.

The pursuit of fertilization alternatives aims to reduce dependence on synthetic fertilizers as the primary source and promote ecologically friendly agriculture by adopting fertilizers derived from wood ash and organominerals. Recent studies show that fertilization with wood ash has significantly contributed to increased soil water retention [3], soil fertility [4], soil biology [5,6], growth and productivity decisively impacting nutritional performance [7], mineral concentration, photosynthetic pigments, and plant secondary metabolites. Wood ash, obtained from biomass burning, is rich in essential macro- and micronutrients, contributing to improved soil quality and consequently crop productivity [8,9].

Another promising approach is the use of organomineral fertilizers, which combine organic sources (such as wood ash) with mineral nutrients [10]. These fertilizers provide effective nutrients to plants and contribute to soil fertility and water retention [11]. The combination of organic and mineral materials allows for a gradual release of nutrients, promoting plant growth in terms of height, tiller number, and leaf area, resulting in high productivity performance [12].

Base saturation levels are an efficient indicator for characterizing soil fertility, and when combined with different types of fertilizers, they help identify those with greater potential to improve soil fertility [13]. According to Rawal et al. [14], base saturation levels help increase the availability of essential nutrients such as potassium, phosphorus, and calcium to plants, compensating for the need for synthetic fertilizers [15], which are produced from non-renewable resources and have significant environmental impacts during their manufacturing [16,17]. Therefore, alternative fertilizers play an essential role in the pursuit of agricultural sustainability.

The proposed hypothesis is that alternative fertilizers like wood ash and organomineral (wood ash + mineral) combined with base saturation levels may promote greater Zuri grass growth compared to mineral fertilizer, while also optimizing water productivity and contributing to sustainability by reducing reliance on synthetic fertilizers. The combination of wood ash-based fertilizers with base saturation is expected to facilitate higher nutritional efficiency for Zuri grass, providing an ideal environment for its growth and productivity. The nutrients released by wood ash-based fertilizers complement those present in the soil, maximizing nutritional availability for the plant.

Quantifying the growth and water productivity of Zuri grass based on the use of wood ash-based alternative fertilizers and base saturation levels will provide relevant information on the importance of these fertilizers in optimizing crop productivity. However, there is an evident scarcity of studies in this area. Nevertheless, this study could yield results for adopting more efficient and sustainable agricultural practices that value waste reuse, such as wood ash, and rational use of water resources.

Given this scenario, the objective of this study is to compare the effects of fertilization with wood ash, organomineral, and mineral fertilizers associated with base saturation levels on the growth and water productivity of Zuri grass.

2. Materials and Methods

2.1. Characterization of the Experimental Site

The study was conducted in a greenhouse belonging to the Institute of Agricultural Sciences of the Federal University of Rondonópolis, located in Rondonópolis, MT, Brazil at geographic coordinates 16°27′49″ S and 54°34′46″ W, at an altitude of 290 m. The experiment took place from January to April 2022.

The greenhouse had a galvanized steel arch structure covered with a 150-micron plastic film. It had a total area of 450 m^2 with a cooling system consisting of an evaporative clay panel and two exhaust fans positioned parallel and opposite to the evaporative panel.

Throughout the experiment, the greenhouse temperature was monitored using a digital thermo-hygrometer installed at a height of 1.5 m during the entire crop cycle. The average minimum and maximum temperatures during the crop cycle were 23.0 °C and 38.6 °C, respectively.

The soil used in the experimental units was classified as Dystrophic Red Oxisol, collected at a depth of 0.00–0.20 m under Cerrado vegetation at the university itself, at geographic coordinates 16°27′35″ S and 54°35′00″ W (Table 1).

Table 1. Physico-chemical characterization of the Dystrophic Red Oxisol collected under Cerrado vegetation at 0–0.2 m depth at the Federal University of Rondonópolis.

pH	SB	CEC	Al	H + Al	MO	V	M	Sand	Silt	Clay
$CaCl_2$	--------------------$cmol_c\ dm^{-3}$--------------------				--------------------%--------------------					
4.3	0.8	5.6	0.6	4.8	2.13	13.5	44.4	33.0	10.0	57.0
P	K	S	Ca	Mg		B	Cu	Fe	Mn	Zn
---------------$mg\ dm^{-3}$---------------			-----$cmol_c\ dm^{-3}$-----			----------------$mg\ dm^{-3}$----------------				
1.5	18.0	2.0	0.5	0.2		0.15	0.2	64.0	21.8	0.7

SB: Sum of bases; CEC: Cation exchange capacity; Al: Aluminum; H: Hydrogen; MO: Organic Matter; V: Base saturation; m: Aluminum saturation; $CaCl_2$: Calcium chloride; P: Phosphorus; K: Potassium; S: Sulfur; Ca: Calcium; Mg: Magnesium; B: Boron; Cu: Copper; Fe: Iron; Mn: Manganese; Zn: Zinc.

The wood ash used in the treatments was obtained from the burning of eucalyptus biomass (*Eucalyptus* sp.) in furnaces of a food industry located in Rondonópolis, MT. The chemical characterization of the wood ash (as fertilizer and corrector) used in the study is shown in Table 2.

Table 2. Chemical analysis of wood ash as corrector and fertilizer.

pH	N	P_2O_5	K_2O	Ca	Mg	SO_4	B	Cu	Fe	Mn	Zn	CaO	MgO	PN	PRNT
$CaCl_2$	--------------------------------$g\ kg^{-1}$--------------------------------													-------%-------	
10.67	4.9	7.9	32.5	49.6	42.0	6.0	0.4	0.1	7.2	0.4	0.2	91.0	65.0	30.0	24.8

N: Total nitrogen; P_2O_5: Phosphorus; K_2O: Potassium; Ca: Calcium; Mg: Magnesium; SO_4: Sulfur; B: Boron; Cu: Copper; Fe: Iron; Mn: Manganese; Zn: Zinc; CaO: Oxide of calcium; MgO: Magnesium oxide; $CaCl_2$: Calcium chloride; PN: Power of neutralization; RPNT: Relative power of neutralization.

2.2. Experimental Design and Treatments

The experimental design was conducted in randomized blocks, with a 3 × 3 factorial arrangement, corresponding to three types of fertilization (Wood ash (WA), Organomineral (OM), and Mineral (M)) associated with three levels of base saturation (V = 0 (natural base saturation of the soil); V = 25%; and V = 50%). Four replications were carried out, totaling 36 experimental units. At the end of the soil incubation period, the factors were combined, resulting in nine treatments, distributed in four blocks (Figure 1).

Each experimental unit consisted of self-irrigating plastic pots with the following dimensions: an external height of 0.18 m; an internal height of 0.14 m; an upper diameter of 0.215 m; a lower diameter of 0.175 m; a pot volume of 5.082 L, and a self-irrigating reservoir volume of 0.96 L.

For the first source of variation, three different types of fertilization were used: WA, OM, and M.

In the treatment composed solely of WA, a fertilization of 24 $g.dm^{-3}$ was recommended [18]. The WA was incubated together with the soil in closed plastic bags for 30 days, with the moisture adjusted to 60% of the soil's maximum water-holding capacity. The incubation aimed to accelerate the soil acidity correction process. The incorporation of WA into the soil occurred 30 days before sowing to avoid possible alkaline effects that could impair the initial growth of the plants.

For the OM treatment, a combination of WA and M fertilizer (Phosphorus (P) + Potassium (K) + micronutrients) was used. This combination consisted of 12 $g.dm^{-3}$ of WA, 75 $mg.dm^{-3}$ of phosphorus (Simple Superphosphate), 50 $mg.dm^{-3}$ of potassium (Potassium Chloride) and 50 $mg.dm^{-3}$ of FTE (boron: 1.8%; copper: 0.85%; sulphur: 3.9%; iron: 3.0%; manganese: 2.0%; molybdenum: 0.1%, and zinc: 9.0%). For WA, we followed half the P and K recommendation of Bezerra et al. [18] and Bonfim-Silva et al. [19], respectively, and for micronutrients, we followed the full recommendation of Bonfim-Silva et al. [19]. This combination was incorporated into the soil on the day of sowing, which occurred in February 2022.

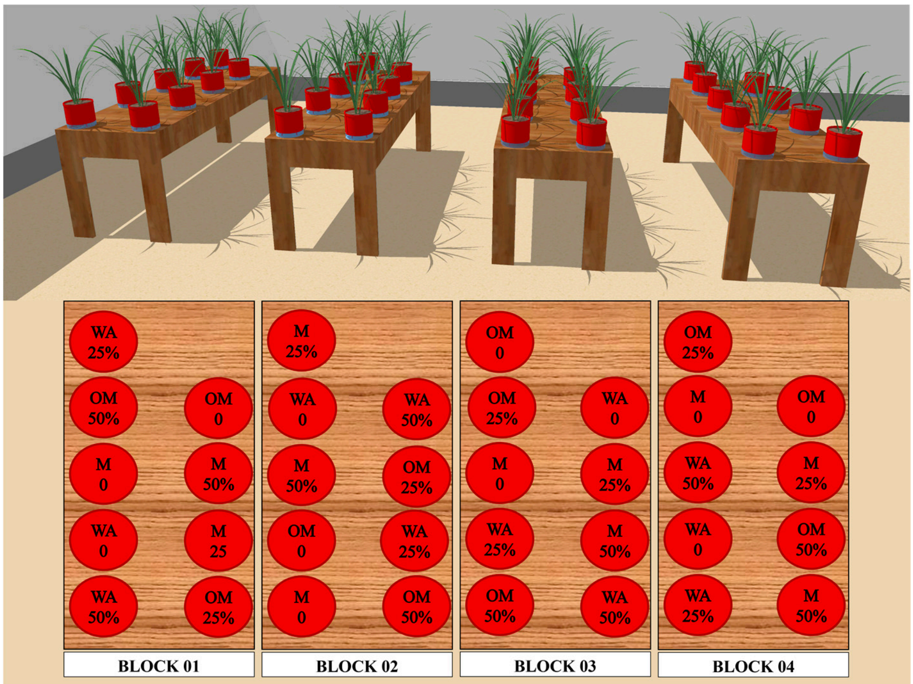

Figure 1. 3D sketch representing the distribution of experimental units on benches in the greenhouse with Zuri grass subjected to different fertilization types (Wood ash (WA), Organomineral (OM), and Mineral (M)) associated with different levels of base saturation (0, 25%, and 50%).

In the M treatment, fertilization was exclusively with mineral fertilizer; 150 mg.dm^{-3} of phosphorus, 100 mg.dm^{-3} of potassium and micronutrients was applied on the day of sowing (February 2022) using the respective sources (Simple Superphosphate, Potassium Chloride and FTE (boron: 1.8%; copper: 0.85%; sulphur: 3.9%; iron: 3.0%; manganese: 2.0%; molybdenum: 0.1%, and zinc: 9.0%)) according to the recommendation of Bonfim-Silva et al. [19].

The second source of variation considered was the base saturation level (V%). The determination of this level was carried out through the base saturation method (V%) using the Lime Requirement formula (LR) according to Sousa and Lobato [20]. The recommendation was 2.4 t ha^{-1} of limestone, which was transformed into g pot^{-1}. To calculate the liming requirement, dolomitic limestone with an RPNT of 86% was used. The goal was to increase the natural base saturation of the soil to 25% and 50%. Based on these calculations, each treatment received its respective proportions (Figure 1).

In the V = 0 treatment (natural base saturation of the soil), the base saturation was not altered, remaining the same as that of the natural soil, i.e., 13.5% according to soil analysis (Table 1). In this case, no limestone was applied to correct the soil.

For the V = 25% and V = 50% treatments, the base saturation was increased to 25% and 50%, respectively. According to Embrapa [21], the ideal recommendation for raising the base saturation for Zuri grass cultivation is 50%. For this, the soil was incubated for 30 days in a plastic bag, adding 0.6 and 1.2 g dm^{-3} of soil, respectively. Additionally, the soil moisture was adjusted to 60% of the maximum water-holding capacity to accelerate the soil acidity correction process.

2.3. Nitrogen Fertilization, Seeding and Thinning

Nitrogen fertilization was common to all treatments. In each growth phase of Zuri grass (when the plant reached 0.10 m in height, 30 days after emergence—first cut, and 60 days after emergence—second cut), the nitrogen fertilization recommendation was 200 mg dm^{-3} [19]. This fertilization was divided into two applications of 1.11 g.pot^{-1} for each experimental unit, with a seven-day interval between them. Urea was used as the nitrogen source, dissolved in 0.05 L of water, and applied close to the soil in all treatments.

A germination test was carried out on the seeds of *Panicum maximum* cv. BRS Zuri (Zuri grass), obtaining a percentage of 80%. For this reason, it was decided to sow a greater number of seeds to guarantee the germination and health of the squad. Therefore, in each experimental unit, approximately 50 seeds of Zuri grass were sown at a depth of 0.02 m. Plant emergence occurred on the fourth day after sowing. During the first fifteen days after emergence, two thinnings were performed. The first thinning was carried out on the seventh day after emergence, leaving approximately 20 plants per pot. The second thinning took place on the fifteenth day after emergence when the plants reached 10 cm in height, retaining the five most vigorous plants in each pot.

2.4. Irrigation Management

The irrigation management of the self-irrigating pots was carried out through capillarity, with water replenishment occurring whenever the water level in the (self-irrigating) reservoir visibly dropped below 75% of its capacity. Irrigation in the self-irrigating pots occurs through capillary action, which maintains the appropriate soil moisture level, preventing both excess and scarcity of water for the plants, which is crucial for their healthy growth and development.

The amount of water consumed by each experimental unit was monitored from plant emergence. The volume of water added to the reservoirs was recorded as the level decreased, allowing the calculation of Zuri grass water consumption throughout the production cycle.

2.5. Analyzed Variables

The variables were analyzed on each cutting occasion. The cuttings occurred at 30, 60, and 90 days after emergence (DAE) of Zuri grass, respectively. The analyzed variables were the chlorophyll index (CI), leaf area (LA), shoot dry mass (SDM), root dry mass (RDM), water consumption (WC), and water productivity (WP).

Before each cutting, the CI was measured using the portable SPAD (Soil Plant Analysis Development) 502-Plus Chlorophyll Meter. Five fully expanded diagnostic plants (+1 and +2) from each experimental unit were selected, and the average was obtained from these readings.

During each cutting, fully expanded leaves were separated from the stems to measure the LA. The LI-3100 AREA METER leaf area integrator was used to obtain the total LA of each experimental unit.

SDM was evaluated at each cutting. The shoot part of the plants (leaves + stems) was placed in a forced ventilation oven at 65 °C for 72 h. After the drying process, the samples were weighed on an analytical balance to obtain the dry mass.

RDM was exclusively evaluated at 90 DAE. After the roots were dried in a forced ventilation oven at 65 °C for 72 h, the RDM was determined by weighing on an analytical balance.

Throughout the experimental period, the volume of water replenished in each experimental unit's reservoir was quantified, from plant emergence to the final cutting at 90 DAE, allowing the calculation of WC for Zuri grass. WP was estimated by relating the SDM and WC for each cutting.

2.6. Statistical Analysis

The experiment data were tested for normality and homoscedasticity. Univariate statistics were used with analysis of variance (ANOVA) measured by the F test. When the effects were significant, the means were compared using the Scott–Knott test at the 5% probability level, using the statistical program SISVAR version 5.8 [22]. Pearson's correlation was also used to verify the contribution of the variables.

3. Results

3.1. Growth Variables of Zuri Grass under Different Fertilization Types and Base Saturation Levels

The summary of the analysis of variance for LA, CI, SDM, and RDM of Zuri grass under different fertilization types and base saturation levels are presented in Table 3.

Table 3. Summary of the analysis of variance with F values for different fertilization types and base saturation levels on leaf area (LA), chlorophyll index (CI), shoot dry mass (SDM) at 30, 60, and 90 days after emergence (DAE), and root dry mass (RDM) at 90 DAE of Zuri grass.

SV	DF	Statistic F									
		LA ($cm^2.pot^{-1}$)			**CI**			**SDM ($g.pot^{-1}$)**			**RDM ($g.pot^{-1}$)**
		30 DAE	**60 DAE**	**90 DAE**	**30 DAE**	**60 DAE**	**90 DAE**	**30 DAE**	**60 DAE**	**90 DAE**	**90 DAE**
Block	3	0.64 ^{ns}	1.35 ^{ns}	1.04 ^{ns}	1.41 ^{ns}	0.37 ^{ns}	1.49 ^{ns}	0.55 ^{ns}	0.14 ^{ns}	0.68 ^{ns}	1.06 ^{ns}
Fertilizing	2	19.01 ***	48.46 ***	19.07 ***	2.14 ^{ns}	27.15 ***	10.54 ***	9.77 ***	37.24 ***	69.34 ***	75.22 ***
Base saturation	2	0.50 ^{ns}	2.51 ^{ns}	0.22 ^{ns}	0.45 ^{ns}	1.17 ^{ns}	1.92 ^{ns}	0.80 ^{ns}	0.12 ^{ns}	0.22 ^{ns}	0.80 ^{ns}
Fertilizing × Base saturation	4	0.45 ^{ns}	1.01 ^{ns}	0.58 ^{ns}	2.40 ^{ns}	0.64 ^{ns}	0.17 ^{ns}	0.22 ^{ns}	0.34 ^{ns}	0.57 ^{ns}	0.15 ^{ns}
Error	24										
CV (%)		16.33	16.71	24.6	8.86	11.13	15.51	19.14	17.31	21,24	19.08
Overall average		3156.97	3731.31	1753.46	39.93	31.13	30.18	18.90	38.74	15.70	30.01

Significance levels: *** $p < 0.001$; ^{ns}: Non-significant. SV: Source of variation. CV: Coefficient of variation. DF: Degrees of freedom.

For the variables LA, CI, SDM, and RDM, there was a significant effect of different fertilization types at all evaluation times (30, 60, and 90 days after emergence—DAE) with a significance level of 0.1%. However, no statistical differences were observed for the base saturation levels, and there was no interaction between the factors of different fertilization types and base saturation levels for any of the studied periods (Table 3).

Significant differences ($p < 0.05$) were observed by the Scott–Knott test among the different fertilization types when analyzing the LA at 30, 60, and 90 DAE (Figure 2a) and the CI at 60 and 90 DAE (Figure 2b) of Zuri grass.

At 30 DAE, the treatment with WA resulted in a significantly larger LA (3906.3 $cm^2.pot^{-1}$) compared to the OM (2797.8 $cm^2.pot^{-1}$) and M (2766.8 $cm^2.pot^{-1}$) treatments. No differences were observed between the OM and M treatments at this early growth stage (Figure 2a).

At 60 and 90 DAE, the WA and OM treatments did not differ from each other, indicating similar effects on Zuri grass LA. However, both treatments differed significantly from the M fertilization treatment. The WA and OM treatments showed LA values of 4564.5 and 4338.8 $cm^2.pot^{-1}$ at 60 DAE, and 1896.3 and 2191.2 $cm^2.pot^{-1}$ at 90 DAE, respectively. In comparison, the M fertilization treatment had lower values, with 2290.6 $cm^2.pot^{-1}$ at 60 DAE and 1142.9 $cm^2.pot^{-1}$ at 90 DAE (Figure 2a). This reflected a percentage difference of 49.8% and 47.2% at 60 DAE and 39.7% and 47.8% at 90 DAE, for WA and OM fertilization, respectively, compared to M fertilizer, directly affecting the forage productivity.

No significant differences were found for the CI variable between treatments at 30 DAE, according to the Scott–Knott test (Figure 2b). However, at 60 DAE, the WA treatment showed a significantly lower CI (25.8 units) compared to those of the OM (31.4 units) and M (36.2 units) treatments (Figure 2b).

At 90 DAE, the WA treatment differed statistically from the OM and M treatments. However, no statistically significant differences were observed between the latter two. The OM and M treatments had CI values of 30.78 and 34.2 units, respectively, while the WA treatment had the lowest index, with 25.5 units (Figure 2b).

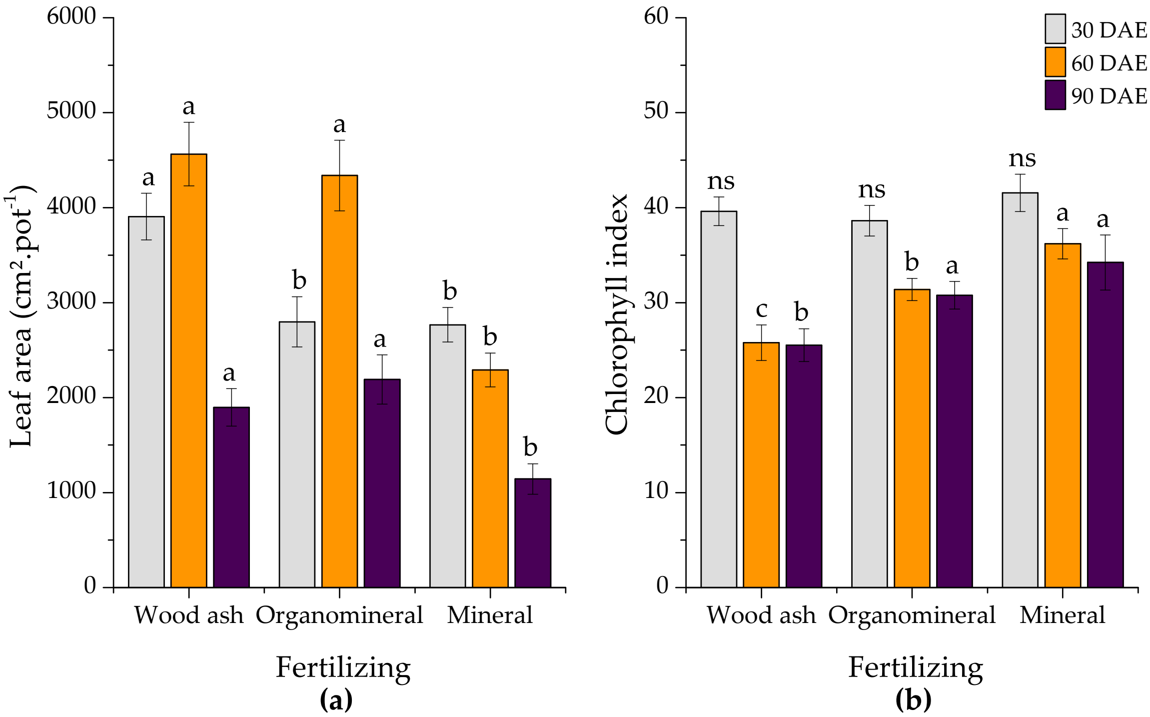

Figure 2. Mean leaf area (LA) ($cm^2.pot^{-1}$) (**a**) and chlorophyll index (CI) (**b**) for the fertilizer type at 30, 60, and 90 DAE (days after emergence) of Zuri grass. Vertical bars indicate standard error of the mean (p = 0.05). Means followed by the same lowercase letter in the different treatments do not differ by the Scott-Knott test at a 5% probability level ^{ns} non-significant.

These results may be related to the correlation effects among the variables analyzed at 30, 60, and 90 DAE (Table 4). It can be observed that there was a negative correlation between CI at 60 and 90 DAE with LA at 30, 60, and 90 DAE at a 5% probability level. It is possible to observe that CI at 60 DAE with LA at 30 DAE has a strong negative correlation, and CI at 60 DAE versus LA at 60 and 90 DAE, respectively, have a moderate negative correlation. For CI at 90 DAE versus LA at 30, 60, and 90 DAE, the correlation is negative and classified as moderate (Table 4). The negative or inverse correlation indicates that high LA values at 30, 60, and 90 DAE correspond to low CI values at 60 and 90 DAE (Figure 2a,b).

Table 4. Pearson correlation between the chlorophyll index (CI) and leaf area (LA) at 30, 60, and 90 days after emergence (DAE) of Zuri grass.

Variables	LA 30	LA 60	LA 90
CI 30	0.08 ^{ns}	−0.19 ^{ns}	0.09 ^{ns}
CI 60	−0.64 *	−0.58 *	−0.48 *
CI 90	−0.44 *	−0.49 *	−0.43 *

* $p < 0.05$; ^{ns}: Non-significant.

When analyzing the SDM at 30, 60, and 90 days after emergence (DAE) of Zuri grass, a significant difference was observed among the different fertilization types (Figure 3).

At 30 DAE, there were no significant differences in SDM between the WA and M treatments at a 5% probability level according to the Scott–Knott test. However, the OM fertilizer treatment showed significantly lower SDM. The highest SDM was observed in the WA and M treatments, with values of 22.1 and 19.1 $g.pot^{-1}$, respectively, while the OM treatment had the lowest value of 15.5 $g.pot^{-1}$ (Figure 3).

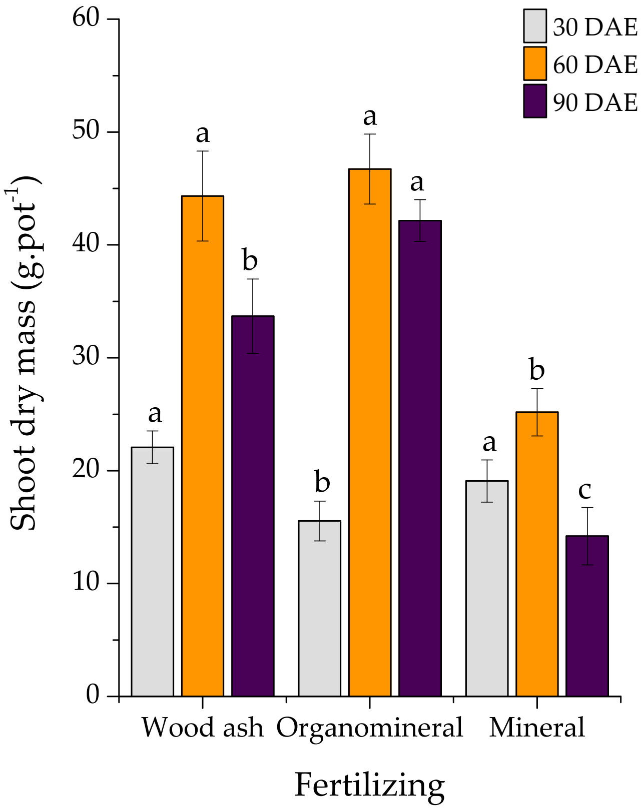

Figure 3. Mean shoot dry mass (SDM) (g.pot^{-1}) for different fertilization types at 30, 60, and 90 DAE (days after emergence) of Zuri grass. Vertical bars indicate standard error of the mean (p = 0.05). Means followed by the same lowercase letter in the different treatments do not differ by the Scott-Knott test at a 5% probability level.

The absence of difference in SDM between the WA and M treatments suggests that, at this early stage of Zuri grass growth (30 DAE), both fertilizers are supplying nutrients equally to the plants. This similarity may be attributed to the process of mineralization and nutrient availability, which can occur similarly for both fertilizer sources at the beginning of cultivation.

However, the lower SDM in the OM treatment suggests that the release of nutrients from this type of fertilizer may have been slower or in smaller amounts at this specific stage of plant development. The process of mineralization and nutrient availability from the OM fertilizer may be requiring more time, as the nutrient supply was limited for the plants at this stage of growth.

For the second cut on the Zuri grass at 60 DAE, there were no significant differences in SDM between the WA and OM treatments, but both differed significantly from the M treatment (Figure 3). The SDM for the WA and OM fertilizers was 44.3 and 46.7 g.pot^{-1}, respectively, while for the M treatment, it was 25.2 g.pot^{-1} (Figure 3). A comparative analysis showed an increase of 43.1% and 46.0% in SDM when using WA and OM fertilizers, respectively, compared to the M fertilizer, which represents an approximately 50% increase.

Significant differences were observed for the SDM variable when subjected to different fertilization types at 90 DAE (Figure 3). The OM fertilizer treatment exhibited the highest SDM with an average value of 42.1 g.pot^{-1}, followed by the WA treatment with 33.7 g.pot^{-1}, while the M fertilizer treatment showed the lowest value of 14.2 g.pot^{-1} (Figure 3). The OM fertilizer increased SDM by 66.3% compared to the M fertilizer.

This finding highlights the importance of providing fertilizers that include WA in their composition, as it supplies nutrients slowly to the plants, allowing them prolonged access to the nutrient. In contrast, fully synthetic fertilizers provide nutrients to the plants rapidly initially and then exhaust the nutrient supply to the soil, compromising plant uptake.

A significant difference was observed among the fertilization types when studying RDM at 90 DAE of Zuri grass cultivation (Figure 4).

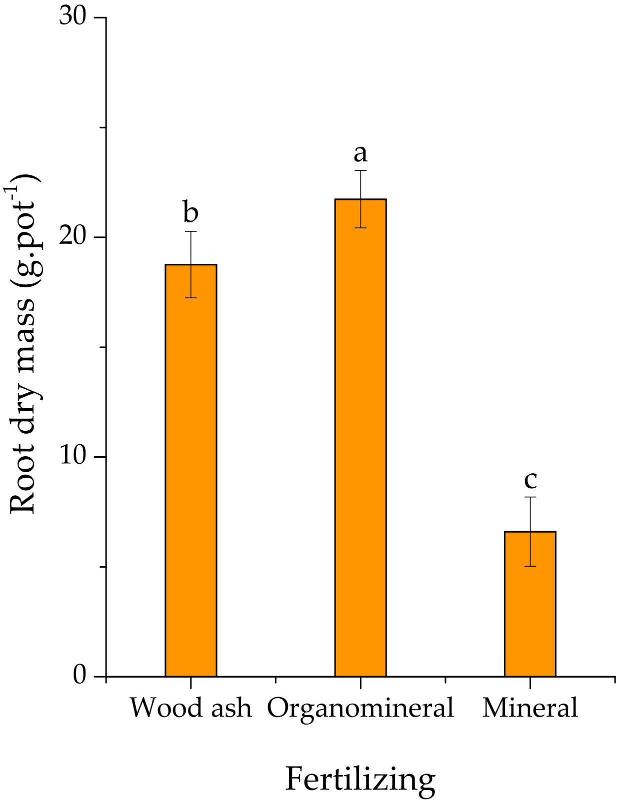

Figure 4. Mean root dry mass (RDM) (g.pot^{-1}) for different fertilization types at 30, 60, and 90 days after emergence (DAE) of Zuri grass. Vertical bars indicate standard error of the mean (p = 0.05).

The treatment with OM fertilizer composed of WA+M showed a significant difference compared to fertilizers that consist of only WA and M fertilizers (N, P, K, plus micronutrients). The OM l treatment exhibited the highest absolute value of RDM, with 21.7 g.pot^{-1}, followed by the WA treatment with 18.8 g.pot^{-1}, and the M fertilizer treatment with 6.6 g.pot^{-1} (Figure 4).

When comparing the M fertilizer treatment to the OM fertilizer treatment, a decrease of 69.6% in RDM production was observed. These results demonstrate the effectiveness of the OM fertilizer in promoting the root growth and development of Zuri grass compared to the WA and M treatments.

This improvement can be attributed to the composition of the OM fertilizer, which includes WA, benefiting the physical, chemical, and biological soil conditions. Additionally, the presence of synthetic nutrients in the OM fertilizer, combined with WA, contributes to a more efficient supply of assimilable nutrients to Zuri grass, resulting in a higher RDM.

These results clearly reflect the correlation between the analyzed variables. When correlating LA at 30 DAE with SDM at 30 and 60 DAE, a positive correlation was observed, indicating that higher LA values reflect higher SDM (Table 5).

LA at 60 and 90 DAE showed a strong and direct correlation with SDM 60, SDM 90, and RDM. However, when studying CI at 60 and 90 DAE versus SDM 60, SDM 90, and RDM, an inverse correlation classified as weak to moderate was observed (Table 5). This means that higher SPAD values result in lower LA of the plant and consequently lower SDM and RDM [23].

Table 5. Pearson correlation between chlorophyll index (CI) and leaf area (LA) versus shoot dry mass (SDM) at 30, 60, and 90 days after emergence (DAE) and root dry mass (RDM) of Zuri grass.

Variables	SDM 30	SDM 60	SDM 90	RDM
LA30	0.58 *	0.41 *	0.29 ^{ns}	0.32 ^{ns}
LA60	−0.03 ^{ns}	0.84 *	0.71 *	0.76 *
LA90	−0.01 ^{ns}	0.72 *	0.84 *	0.76 *
CI 30	0.20 ^{ns}	−0.20 ^{ns}	−0.21 ^{ns}	−0.25 ^{ns}
CI 60	−0.37 *	−0.60 *	−0.56 *	−0.58 *
CI 90	−0.22ns	−0.44 *	−0.37 *	−0.39 *

* $p < 0.05$; ^{ns}: Non-significant.

3.2. Water Consumption and Water Productivity of Zuri Grass under Different Fertilization Types and Base Saturation Levels

The summary of the analysis of variance for WC and WP of Zuri grass at 30, 60, and 90 DAE under different fertilization types and base saturation levels are shown in Table 6.

Table 6. Summary of the analysis of variance with F values for different fertilization types and base saturation levels in water consumption (WC) and water productivity (WP) at 30, 60, and 90 days after emergence (DAE) of Zuri grass.

SD	DF	Statistic F					
		WC (L.pot^{-1})			WP (g.L^{-1})		
		30 DAE	60 DAE	90 DAE	30 DAE	60 DAE	90 DAE
Block	3	0.44 ^{ns}	0.16 ^{ns}	1.83 ^{ns}	0.36 ^{ns}	0.21 ^{ns}	0.77 ^{ns}
Fertilizing	2	4.95 *	4.71 *	49.74 ***	3.27 ^{ns}	53.21 ***	55.77 ***
Base saturation	2	0.30 ^{ns}	0.84 ^{ns}	1.39 ^{ns}	0.38 ^{ns}	0.35 ^{ns}	1.64 ^{ns}
Fertilizing × Base saturation	4	0.94 ^{ns}	1.56 ^{ns}	0.12 ^{ns}	0.47 ^{ns}	1.43 ^{ns}	0.23 ^{ns}
Error	24						
CV (%)		11.04	9.29	13.29	19.93	12.21	12.76
Overall average		6.07	9.31	5.53	3.12	4.12	5.16

Significance levels: * $0.01 < p < 0.05$; *** $p < 0.001$; ^{ns}: Non-significant. SV: Source of variation. CV: Coefficient of variation. DF: Degrees of freedom.

When studying WC and WP of Zuri grass, a significant effect of fertilization types was observed at different evaluation times (Table 6). For WC, the effect was significant at 30 and 60 DAE at a 5% significance level and at 90 DAE at a 0.1% significance level (Table 6). Regarding WP, a significant effect of fertilization types was observed at 60 and 90 DAE at a 0.1% probability level according to F statistics. When analyzing the isolated effect of base saturation levels, no significant effect was found for WC and WP at any of the evaluation times. Additionally, there was no interaction between fertilization types and base saturation levels for these variables (Table 6).

Significant differences at a 5% probability level according to the Scott–Knott test were observed among the fertilization types when analyzing WC at 30, 60, and 90 DAE (Figure 5a) and WP at 60 and 90 DAE (Figure 5b) of Zuri grass.

At 30 DAE, no significant differences in WC were observed between the WA and M fertilizers. However, the OM treatment showed a significant difference from the others, with the WA and M treatments recording the highest WC in absolute terms, corresponding to 6.4 and 6.2 L.pot^{-1}, respectively, while the OM treatment had the lowest consumption, with 5.6 L.pot^{-1} (Figure 5a).

At 60 and 90 DAE (Figure 5a), the WA treatment did not show a significant difference compared to the OM treatment but differed significantly from the M fertilizer treatment at a 5% probability level according to the Scott–Knott test. WC in the WA and OM treatments was 9.6 L.pot^{-1} at 60 DAE and 6.2 L.pot^{-1} at 90 DAE. In the M fertilizer treatments, WC values were 8.7 L.pot^{-1} at 60 DAE and 3.8 L.pot^{-1} at 90 DAE.

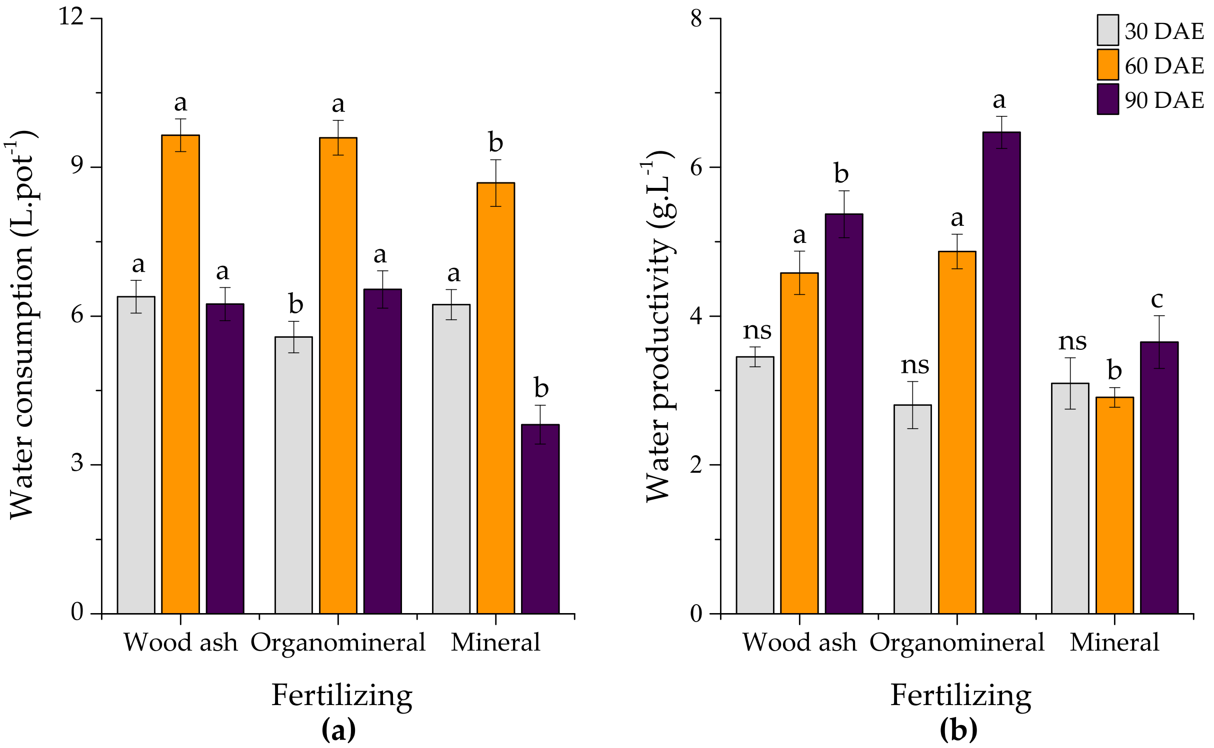

Figure 5. Mean water consumption (L.pot^{-1}) (**a**) and water productivity (g.L^{-1}) (**b**) for different fertilization types at 30, 60, and 90 DAE (days after emergence) of Zuri grass. Vertical bars indicate standard error of the mean (p = 0.05). Vertical bars indicate standard error of the mean (p = 0.05). Means followed by the same lowercase letter in the different treatments do not differ by the Scott-Knott test at a 5% probability level.

These data indicate that the WA-based and OM fertilizers had similar WC, while the M fertilizer treatment showed lower consumption, especially at 90 DAE. Thus, it can be noted that alternative fertilizers are an important tool that contributes significantly to the efficient management of irrigation and the optimization of water resources in Zuri grass cultivation.

When studying WP, no significant difference was observed at 30 DAE for the fertilization types. In other words, the fertilizers consisting of WA, OM, and M fertilizers had the same WP (Figure 5b).

At 60 DAE, the WA did not differ significantly from the OM treatment but differed significantly at a 5% probability level according to the Scott–Knott test from the M fertilizer treatment. WP for WA and OM was 4.6 and 4.9 g.L^{-1}, respectively, while in the M fertilizer treatments, the values were 2.9 g.L^{-1}. There was an increase of 37.0% and 40.8% in WP in the WA and OM treatments, respectively, compared to the M fertilizer (Figure 5b). This means that for every 1 L of water applied in the WA and OM fertilizer treatments, it generates a return in terms of dry biomass production of 4.6 and 4.9 g in each pot, representing an increase of approximately 39% compared to the M fertilizer treatment using the same amount of water.

At 90 DAE, the OM fertilizer treatment differed significantly from the WA and M treatments. The OM treatment had the highest absolute value, 6.5 g.L^{-1}, followed by the WA treatment with 5.4 g.L^{-1}, and the M fertilizer treatment with 3.7 g.L^{-1}. Comparing the M fertilizer treatment with the OM treatment, there was a 43.1% reduction in WP. These data indicate that fertilizers containing WA in their composition are more efficient in utilizing and converting water into SDM. In other words, alternative fertilizers significantly contribute to the rational use of water by plants, allowing for greater sustainability in the use of fertilizers and water resources.

When correlating WC with variables CI, LA, SDM (30, 60, and 90 DAE), and RDM at 90 DAE, a moderate positive correlation was observed between WC and CI, LA, and SDM at 30 DAE. This indicates that as WC increased, the CI, LA, and SDM at 30 DAE also increased (Table 7). On the other hand, the correlation between WC at 60 DAE and CI at 60 DAE showed a moderate negative correlation, meaning that when WC increased, the CI decreased, and consequently, the LA of Zuri grass increased.

Table 7. Pearson correlation between water consumption (WC) and water productivity (WP) (30, 60, and 90 DAE) versus chlorophyll index (CI); leaf area (LA), shoot dry mass (SDM) (30, 60, and 90 DAE), and root dry mass (RDM) of Zuri grass.

Variables	CI 30	CI 60	CI 90	LA 30	LA 60	LA 90	SDM 30	SDM 60	SDM 90	RDM
WC 30	0.40 *	−0.20 ^{ns}	−0.05 ^{ns}	0.49 *	−0.20 ^{ns}	−0.09 ^{ns}	0.49 *	−0.10 ^{ns}	−0.15 ^{ns}	−0.12 ^{ns}
WC 60	−0.12 ^{ns}	−0.40 *	−0.29 ^{ns}	0.39 *	0.43 *	0.29 ^{ns}	−0.04 ^{ns}	0.66 *	0.51 *	0.55 *
WC 90	−0.21 ^{ns}	−0.64 *	−0.46 *	0.35 *	0.70 *	0.77 *	0.08 ^{ns}	0.76 *	0.94 *	0.94 *
WP 30	−0.01 ^{ns}	−0.25 ^{ns}	−0.22 ^{ns}	0.34 *	0.04 ^{ns}	0.03 ^{ns}	0.85 *	−0.01 ^{ns}	−0.16 ^{ns}	−0.01 ^{ns}
WP 60	−0.21 ^{ns}	−0.57 *	−0.43 *	0.33 ^{ns}	0.85 *	0.78 *	−0.06 ^{ns}	0.96 *	0.81 *	0.83 *
WP 90	−0.22 ^{ns}	−0.47 *	−0.27 ^{ns}	0.23 ^{ns}	0.68 *	0.80 *	−0.16 ^{ns}	0.81 *	0.94 *	0.87 *

* $p < 0.05$; ^{ns}: Non-significant.

Increasing WC at 60 DAE had a decisive contribution to the increase in LA at 30 and 60 DAE, consequently leading to an increase in SDM at 60 and 90 DAE, as well as RDM. This represents a direct effect of one variable on the response of the other, classifying the correlation as moderate (Table 7).

At 90 DAE, as WC increased in plants, it significantly reduced the CI at 60 and 90 DAE. However, there was an increase in LA at 30, 60, and 90 DAE, as well as in SDM (60 and 90 DAE) and RDM (Table 7).

When correlating WP at 60 and 90 DAE with variables LA and SDM at different evaluation times, as well as RDM at 90 DAE, the highest correlations ranged from strong to very strong (Table 7). These data confirm that growth variables directly influence WC and WP of Zuri grass and can be used as decision-making tools in the efficient management of both fertilization and water for the crop.

4. Discussion

Over the years, the excessive use of synthetic fertilizers has caused serious environmental problems. Research focused on alternative fertilizers such as WA, and the WA+M (OM) combination is essential. However, introducing these new fertilizers to Zuri grass cultivation is a challenge. Testing alternative fertilizers with different levels of base saturation is an interesting alternative that can reduce dependence on synthetic fertilizers, lower production costs, and minimize environmental impacts.

The results indicate that WA and OM promote positive growth in Zuri grass in different periods. These fertilizers increase LA, CI, SDM, and RDM compared to M. They also improve the efficiency of water use by Zuri grass, decreasing WC and increasing WP.

In the LA analysis of Zuri grass, at 30 DAE, the WA treatment showed a significantly higher LA. In the subsequent phases (60 and 90 DAE), both the WA and OM treatments had higher LA than the M fertilizer treatments.

LA is crucial for plant growth and development, as it is directly related to the capture of sunlight and photosynthesis [24], an essential process for producing energy and biomass [25]. Therefore, the results indicate that fertilizers containing WA, alone or in combination with synthetic fertilizer (OM), can increase the development of LA in Zuri grass, positively impacting productivity and crop performance.

The main nutrient in WA that increases leaf production in grasses is K, along with Ca and Mg, which corrects soil pH and removes Al toxicity, gradually releasing essential nutrients for plant growth. Available K directly influences the development and production of plant leaves, affecting growth rate and photosynthesis [26]. When enough K is in the soil, plants produce and maintain more leaves, resulting in greater LA.

The CI did not differ significantly at 30 DAE between treatments, but at 60 and 90 DAE, the WA treatment resulted in a significantly lower CI than the OM and M treatments. This suggests a negative effect of WA on the chlorophyll content of the plants. This effect can be attributed to the increase in LA observed in the WA treatment at 60 and 90 DAE, which can dilute the chlorophyll in the leaves, decreasing its concentration. It is important to note that there was an inverse relationship between the dilution of CI concerning the LA of the plants, i.e., plants with fewer leaves tend to have higher CI values, and vice versa [23].

When analyzing the application of WA, OM, and M fertilizers to promote the growth of arugula (*Eruca sativa* Miller) at different base saturations in Oxisol [27], similar results were found in this study about CI. According to Bonfim-Silva et al. [27], in the WA treatment, the CI values were 10.53 and 17.65 for base saturation of 50% and 80%, respectively. In the OM treatment, the values were 50.80 and 45.93, while in the M treatment, they were 29.55 and 41.20 for the same base saturation levels. These results confirm the findings of this study, showing that the effects of fertilizers were similar, even on different crops, and that WA resulted in the lowest CI.

Photosynthetic capacity is optimized by increasing the availability of nitrogen (N), as it is essential for forming chlorophyll [28]. CI is used to assess the nutritional status of N in plants by measuring the green pigments in the leaves [29]. CI values above 30 indicate the good nutritional status of Zuri grass. However, in the WA treatments, the CI values were lower, showing a clear deficiency of this nutrient, despite the application of 200 $mg.dm^{-3}$ of N per cut of the Zuri grass, as in the other treatments.

It is important to note that Zuri grass overgrows in terms of LA, height, stem diameter, and number of tillers, which contributes to greater assimilation and utilization of N [30]. However, the deficiency was still evident in the WA treatment, indicating that the plant may need more of this nutrient.

It was also observed that OM fertilizer showed similar efficiency to that of the M fertilizer. This indicates that WA, as a component of OM fertilizer, contributed to better use of the N applied. It is important to note that N plays a crucial role in various processes, such as growth, LA expansion, and biomass production [31,32].

The lack of significant differences in SDM at 30 DAE between the treatments is due to the fact that the M fertilizer provides nutrients more quickly at this early stage of growth, meeting the crop's initial needs. On the other hand, WA releases nutrients gradually as the organic matter mineralizes, benefiting later improvements in crop development [33]. Therefore, in the first 30 DAE, WA is still reactive in the soil in a similar way to M/synthetic fertilizer, while nutrient absorption in the OM treatment is slower and more gradual during this initial phase.

At 60 and 90 DAE, both WA and OM had a positive effect on SDM, resulting in greater biomass compared to M fertilizer alone. The OM fertilizer showed greater efficiency in biomass production, highlighting the importance of combining organic nutrients from WA with synthetic mineral fertilizers to stimulate the growth of Zuri grass. At 90 days after applying the treatments, it is clear that OM fertilizer is capable of providing long-term nutrients to Zuri grass, resulting in greater SDM production.

The increase in the SDM of plants depends on several factors, especially the availability of nutrients and when considering the aerial part of the plants [23]. These results are similar to those of Fernandes et al. [34], who studied the dry matter productivity of black oats (*Avena 14trigose*) and found higher SDM with OM fertilization (based on liquid pig manure) compared to fluid mineral fertilization (soluble monoammonium phosphate) and solid mineral fertilization (triple superphosphate). This reinforces the importance of OM fertilizers in various crops, increasing the production of SDM.

OM fertilizer had a higher RDM than WA and M. The presence of nutrients from organic fertilizers (WA) in this treatment provided a balanced and continuous supply of essential nutrients for root growth. In addition, the organic matter in OM fertilizers improved soil properties, including water retention, density, porosity, and aeration [3], as well as soil chemistry and biology [6], benefiting Zuri grass root growth.

The WA and M fertilizer treatments resulted in lower RDM than obtained during the OM treatment, indicating that WA requires nutrient supplementation to meet the crop's needs, while the M fertilizer provides nutrients immediately without creating reserves in the soil. This results in a faster nutrient deficiency than that observed with the other fertilizers used in this study.

The most important nutrients for root growth are P and K, present in both M and WA fertilizers, as they stimulate root development. This explains the increase in RDM when these fertilizers are combined (WA+M). P promotes root growth, alters their morphology, and increases the proliferation and elongation of root hairs, improving the absorption of water and nutrients [35,36]. Therefore, the P present in WA, which is also part of the OM fertilizer studied, favors the growth of Zuri grass roots in this type of fertilization.

The increase in root mass improves the stability of the root system, increases nutrient absorption due to the larger area explored, and increases the volume of soil occupied by the roots [37], which benefits the aerial part of the plants. In addition, RDM is related to the re-sprouting potential of forage grasses, as the roots and base of the stalks have organic carbohydrate reserves. These reserves are used as a source of energy when the residue is limited after each cut [38]. This means that the greater the amount of root, the greater the possibility of regrowth and tillering of the Zuri grass. The production capacity of the aerial part of a plant depends on the interaction with the root system since the roots are responsible for absorbing nutrients and water [39].

Concerning WC, Zuri grass showed greater WC when fertilized with WA or WA+M compared to fertilizer M. As LA increased, WC and SDM also increased, highlighting the effectiveness of combining organic and mineral nutrients. The exception was at 30 DAE due to the early stage of development and release of nutrients by the different fertilizers.

The higher WC in the WA and OM treatments (above 9 L.pot^{-1} at 60 DAE and above 6 L.pot^{-1} at 90 DAE) can be attributed to the greater LA, SDM, and RDM development in these treatments. As the plants grow, evapotranspiration increases, resulting in greater WC. This is related to adequate nutrients that promote the assimilation of more nutrients by the plant, favoring the development of LA and, consequently, greater dry mass [40].

WA can improve water retention capacity and nutrient availability due to its property of retaining water [5,41]. Soils fertilized with WA have more water than those fertilized only with conventional mineral fertilizers [42]. This water retention not only prolongs the water availability for plants, but can also reduce the frequency or interval of irrigation, saving water and benefiting farmers.

At 30 DAE, there were no differences in WP between the treatments, but at 60 and 90 DAE, the treatments with WA and OM showed higher WP compared to fertilizer M. This highlights the benefits of combining organic and mineral nutrients (OM) in optimizing the WP of Zuri grass. Specifically, at 60 DAE, the combination of organic and mineral nutrients resulted in a gain of 4.9 g of SDM per liter of water applied to the soil. At 90 DAE, these gains were even more significant, reaching 6.5 g of SDM per liter of water applied via capillarity.

These results emphasize the importance of an integrated approach to plant nutrition, combining organic and mineral nutrients in a balanced way to improve soil fertility. This benefits the growth of Zuri grass, increasing the efficiency with which it uses the available water and, consequently, its productivity.

The higher WP is related to the greater availability of water in the soil fertilized with WA, which contributes to water retention in the soil and greater availability to the plants during their growth cycle. Therefore, Zuri grass showed better growth and WP when fertilized exclusively with WA or in combination with the M fertilizer.

WP indicates the relationship between the biomass produced by the plant in relation to the amount of water supplied during the crop cycle [43,44]. Crops that can produce more biomass with less water are considered more productive regarding the efficient use of available water resources [42]. This results in increased yields of water savings and contributes to the conservation of water resources and sustainability since plants can make better use of the available water and convert it into biomass or productivity [45]. To this end, strategies such as selecting cultivars adapted to water availability and proper soil and fertilization management are adopted [46]. These measures improve crop WP, optimizing the use of this vital resource.

Base saturation levels did not affect the growth and water productivity of Zuri grass in isolation, nor did they interact with fertilizer types. Even though a strategy of combining alternative fertilizers with different base saturation levels was seen as sustainable, the results show that these variations in base saturation levels did not significantly impact plant development.

One possible explanation is that alternative fertilizers, such as WA and the WA+M combination, provide nutrients in a balanced and adequate way for Zuri grass, regardless of the base saturation levels in the soil. This indicates that these specific factors did not limit the plant, as it obtained the nutrients necessary for its growth from alternative fertilizers. For example, WA can increase the soil's cation exchange capacity (CEC), helping to maintain the soil's pH and supplying the plant's nutritional needs [5,26].

It is important to note that the lack of effect of base saturation levels does not invalidate the importance of alternative fertilizers in growing Zuri grass. On the contrary, the study confirms that these fertilizers were effective in promoting an increase in LA, CI, SDM, and RDM, as well as improving the efficiency of water use by the plants. Combining alternative fertilizers with different base saturation levels remains a viable strategy for reducing dependence on synthetic fertilizers and mitigating environmental impacts.

The results of this study confirm the initial hypothesis that the use of alternative WA-based fertilizers and the WA+M combination, along with base saturation levels, can be effective and advantageous strategies for growing Zuri grass, significantly improving its growth and WP. Adopting this practice can help promote more balanced, economically viable, and environmentally responsible production systems. However, more research is needed to understand the OM fertilizer produced from WA and its relationship to soil and plant benefits.

5. Conclusions

1. The OM fertilizer (WA+M) is an alternative that reduces dependence on synthetic fertilizers and helps mitigate environmental impacts.
2. Base saturation levels did not individually or interactively influence the growth and water productivity of Zuri grass throughout the crop cycles, regardless of the types of fertilizers used.
3. For every 1 L of water applied, an average of 5.0 g of Zuri grass dry matter was produced with WA and WA combined with mineral fertilizer (OM).
4. It is noteworthy that the OM fertilization showed significant increases of 50% in leaf area, 66% in shoot dry mass, 70% in root dry mass, 41% in water consumption, and 50% in water productivity when compared to synthetic fertilizer.
5. The OM fertilizer obtained from WA was a differentiator regarding improvements in the long-term supply of nutrients to crops.

Author Contributions: Conceptualization, N.P.R.d.O. and E.M.B.-S.; methodology, N.P.R.d.O. and P.F.d.S.; software, N.P.R.d.O. and P.F.d.S.; validation, E.M.B.-S., N.P.R.d.O., T.J.A.d.S., M.K., S.L.G. and T.F.D.; formal analysis, R.A.d.S.R., L.A.M.M. and A.S.C.C.; investigation, E.M.B.-S.; resources, N.P.R.d.O. and E.M.B.-S.; data curation, N.P.R.d.O. and P.F.d.S.; writing—original draft preparation, N.P.R.d.O.; writing—review and editing, N.P.R.d.O. and E.M.B.-S.; visualization, R.A.d.S.R., L.A.M.M. and A.S.C.C.; supervision, E.M.B.-S.; project administration, E.M.B.-S.; funding acquisition, E.M.B.-S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Coordination for the Improvement of Higher Education Personnel-CAPES, grant number 88887.645122/2021-00.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: All the data reported here are available from the authors upon request.

Acknowledgments: This research was funded by Coordination for the Improvement of Higher Education Personnel-CAPES, grant number 88887.645122/2021-00. The Federal University of Rondonópolis (UFR) and the Postgraduate Program in Agricultural Engineering (PPGEagri) for the academic infrastructure and conditions for implementing, conducting and analyzing the research.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Tahat, M.M.; Alananbeh, K.M.; Othman, Y.A.; Leskovar, D.I. Soil health and sustainable agriculture. *Sustainability* **2020**, *12*, 489. [CrossRef]
2. da Silva, E.B.; de Souza, C.M.S.; Furtado, R.N.; Lopes, M.N.; de Melo, B.M. Chemical composition of *Panicum maximum* 'BRS Zuri' subjected to levels of salinity and irrigation depths. *Rev. Ciênc. Agron.* **2020**, *51*, e20175997. [CrossRef]
3. Duarte, T.F.; Bonfim-Silva, E.M.; da Silva, T.J.A.; Koetz, M.; Lima, G.F. Physical-hydric properties of Oxisol and Quartzipsamment associated with the application of wood ash. *Rev. Bras. Eng. Agríc. Ambient.* **2023**, *27*, 188–194. [CrossRef]
4. Moragues-Saitua, L.; Arias-González, A.; Blanco, F.; Benito-Carnero, G.; Gartzia-Bengoetxea, N. Effects of biochar and wood ash amendments in the soil-water-plant environment of two temperate forest plantations. *Front. For. Glob. Chang.* **2023**, *5*, 87821. [CrossRef]
5. Johan, P.D.; Ahmed, O.H.; Omar, L.; Hasbullah, N.A. Phosphorus transformation in soils following co-application of charcoal and wood ash. *Agronomy* **2021**, *11*, 2010. [CrossRef]
6. Oliveira, W.C.M.; Bonfim-Silva, E.M.; Ferraz, A.P.F.; Guimarães, S.L.; Silva, T.J.A.; Duarte, T.F. Soil quality indicators for *Urochloa brizantha* fertilized with wood ash. *Rev. Bras. Eng. Agríc. Ambient.* **2023**, *27*, 241–249. [CrossRef]
7. Bonfim-Silva, E.M.; Martinez-Santos, T.; da Silva, T.J.A.; Alves, R.D.S.; Pinheiro, E.A.R.; Duarte, T.F. Wood ash as a vegetative-growth promoter in soils with subsurface compaction. *Rev. Bras. Eng. Agríc. Ambient.* **2022**, *26*, 258–265. [CrossRef]
8. Szpunar-Krok, E.; Szostek, M.; Pawlak, R.; Gorzelany, J.; Migut, D. Effect of fertilisation with ash from biomass combustion on the mechanical properties of potato tubers (*Solanum tuberosum* L.) grown in two types of soil. *Agronomy* **2022**, *12*, 379. [CrossRef]
9. Bonfim-Silva, E.M.; Costa, A.S.; José, J.V.; Ferraz, A.P.F.; Damasceno, A.P.A.B.; Silva, T.J.A. Correction of acidity of a brazilian Cerrado Oxisol with limestone and wood ash on the initial growth of cowpea. *Agric. Sci.* **2019**, *10*, 841–851. [CrossRef]
10. Bouhia, Y.; Hafidi, M.; Ouhdouch, Y.; Boukhari, M.M.; Mphatso, C.; Zeroual, Y.; Lyamlouli, K. Conversion of waste into organo-mineral fertilizers: Current technological trends and prospects. *Rev. Environ. Sci. Biotechnol.* **2022**, *21*, 425–446. [CrossRef]
11. Magela, M.L.M.; Camargo, R.; Lana, R.M.Q.; Miranda, M.C.C. Application of organomineral fertilizers sourced from filter cake and sewage sludge can affect nutrients and heavy metals in soil during early development of maize. *Aust. J. Crop Sci.* **2019**, *13*, 863–873. [CrossRef]
12. Bouhia, Y.; Hafidi, M.; Ouhdouch, Y.; Zeroual, Y.; Lyamlouli, K. Organo-Mineral fertilization based on olive waste sludge compost and various phosphate sources improves phosphorus agronomic efficiency, *Zea mays* agro-physiological traits, and water availability. *Agronomy* **2023**, *13*, 249. [CrossRef]
13. Bouajila, K.; Hechmi, S.; Mechri, M.; Jeddi, F.B.; Jedidi, N. Short-term effects of sulla residues and farmyard manure amendments on soil properties: Cation exchange capacity (CEC), base cations (BC), and percentage base saturation (PBS). *Arab. J. Geosci.* **2023**, *16*, 410. [CrossRef]
14. Rawal, A.; Chakraborty, S.; Li, B.; Lewis, K.; Godoy, M.; Paulette, L.; Weindorf, D.C. Determination of base saturation percentage in agricultural soils via portable X-ray fluorescence spectrometer. *Geoderma* **2019**, *338*, 375–382. [CrossRef]
15. Javed, T.; Indu, I.; Singhal, R.K.; Shabbir, R.; Shah, A.N.; Kumar, P.; Jinger, D.; Dharmappa, P.M.; Shad, M.A.; Saha, D.; et al. Recent advances in agronomic and physio-molecular approaches for improving nitrogen use efficiency in crop plants. *Front. Plant Sci.* **2022**, *13*, 877544. [CrossRef]
16. Guo, L.; Li, H.; Cao, X.; Cao, A.; Huang, M. Effect of agricultural subsidies on the use of chemical fertilizer. *J. Environ. Manag.* **2021**, *299*, 113621. [CrossRef]
17. Pahalvi, H.N.; Rafiya, L.; Rashid, S.; Nisar, B.; Kamili, A.N. Chemical fertilizers and their impact on soil health. In *Microbiota and Biofertilizers*; Dar, G.H., Bhat, R.A., Mehmood, M.A., Hakeem, K.R., Eds.; Springer: Berlin/Heidelberg, Germany, 2021; Volume 2, pp. 1–20. [CrossRef]
18. Bezerra, M.D.L.; Bonfim-Silva, E.M.; Silva, T.J.A.; Ferraz, A.P.F.; Damasceno, A.P.A.B. Phytometric characteristics and chlorophyll index of "Paiaguás" grass (*Urochloa brizantha*) as a function of wood ash doses and soil water stress. *Aust. J. Crop Sci.* **2019**, *13*, 1883–1891. [CrossRef]

19. Bonfim-Silva, E.M.; Oliveira, N.P.R.; Mazero, H.M.; Alves, D.J.; Oliveira, J.R.; Silva, T.J.A. Production and morphophysiological responses of *Panicum maximum* cv. BRS Zuri to water availability. *Aust. J. Crop Sci.* **2022**, *16*, 1203–1211. [CrossRef]
20. Sousa, D.M.G.; Lobato, E. Correção da acidez do solo. In *Cerrado: Correção do Solo e Adubação*, 2nd ed.; Sousa, D.M.G., Lobato, E., Eds.; Embrapa Informação Tecnológica: Brasília, Brazil, 2004; pp. 81–96.
21. Embrapa—Empresa Brasileira de Pesquisa Agropecuária. *BRS Zuri, Produção e Resistência Para a Pecuária*; Embrapa Gado de Corte: Campo Grande, Brazil, 2014; pp. 1–2. Available online: https://ainfo.cnptia.embrapa.br/digital/bitstream/item/123642/1/Folder-Zuri-Final-2014.pdf (accessed on 27 July 2023).
22. Ferreira, D.F. Sisvar: A computer analysis system to fixed effects split plot type designs. *Rev. Bras. Biom.* **2019**, *37*, 529–535. [CrossRef]
23. Taiz, L.; Zeiger, E.; Møller, I.M.; Murphy, A. *Fisiologia e Desenvolvimento Vegetal*, 6th ed.; Artmed: Porto Alegre, Brazil, 2017; p. 888.
24. Tan, T.; Li, S.; Fan, Y.; Wang, Z.; Raza, M.A.; Shafiq, I.; Wang, B.; Wu, X.; Yong, T.; Wang, X.; et al. Far-red light: A regulator of plant morphology and photosynthetic capacity. *Crop J.* **2022**, *10*, 300–309. [CrossRef]
25. Gheith, E.M.S.; El-Badry, O.Z.; Lamlom, S.F.; Ali, H.M.; Siddiqui, M.H.; Ghareeb, R.Y.; El-Sheikh, M.H.; Jebril, J.; Abdelsalam, N.R.; Kandil, E.E. Maize (*Zea mays* L.) productivity and nitrogen use efficiency in response to nitrogen application levels and time. *Front. Plant Sci.* **2022**, *13*, 941343. [CrossRef] [PubMed]
26. Paramisparam, P.; Ahmed, O.H.; Omar, L.; Ch'ng, H.Y.; Johan, P.D.; Hamidi, N.H. Co-application of charcoal and wood ash to improve potassium availability in tropical mineral acid soils. *Agronomy* **2021**, *11*, 2081. [CrossRef]
27. Bonfim-Silva, E.M.; Oliveira, E.S.; Bezerra, M.D.L.; Castañon, T.H.F.M.; Fenner, W.; Silva, T.J.A. Application of wood ash, organomineral and mineral fertilizers to increase the growth of arugula (*Eruca sativa* Miller) at different base saturation on Oxisol. *J. Exper. Agricul. Int.* **2017**, *17*, 1–6. [CrossRef]
28. Xiong, D.; Chen, J.; Yu, T.; Gao, W.; Ling, X.; Li, Y.; Peng, S.; Huang, J. SPAD-based leaf nitrogen estimation is impacted by environmental factors and crop leaf characteristics. *Sci. Rep.* **2015**, *5*, 13389. [CrossRef]
29. Carvalho, C.L.M.; Duarte, A.N.; Hungria, M.; Nogueira, M.A.; Moreira, A.; Soares Filho, C.V. Nitrogen in shoots, number of tillers, biomass yield and nutritive value of Zuri guinea grass inoculated with plant-growth promoting bacteria. *Int. J. Innov. Educ. Res.* **2020**, *8*, 437–463.
30. Shibaeva, T.G.; Mamaev, A.V.; Sherudilo, E.G. Evaluation of a SPAD-502 Plus Chlorophyll Meter to estimate chlorophyll content in leaves with interveinal chlorosis. *Russ. J. Plant Physiol.* **2020**, *67*, 690–696. [CrossRef]
31. Anas, M.; Liao, F.; Verma, K.K.; Sarwar, M.A.; Mahmood, A.; Chen, Z.L.; Li, Q.; Zeng, X.P.; Liu, Y.; Li, Y.R. Fate of nitrogen in agriculture and environment: Agronomic, eco-physiological and molecular approaches to improve nitrogen use efficiency. *Biol. Res.* **2020**, *53*, 47. [CrossRef]
32. Chattha, M.S.; Ali, Q.; Haroon, M.; Afzal, M.J.; Javed, T.; Hussain, S.; Mahmood, T.; Solanki, M.K.; Umar, A.; Abbas, W.; et al. Enhancement of nitrogen use efficiency through agronomic and molecular based approaches in cotton. *Front. Plant Sci.* **2022**, *13*, 994306. [CrossRef]
33. Kominko, H.; Gorazda, K.; Wzorek, Z. The possibility of organo-mineral fertilizer production from sewage sludge. *Waste Biomass Valor.* **2017**, *8*, 1781–1791. [CrossRef]
34. Fernandes, D.M.; Grohskopf, M.A.; Gomes, E.R.; Ferreira, N.R.; Büll, L.T. Fósforo na solução do solo em resposta à aplicação de fertilizantes fluidos mineral e organomineral. *Irriga* **2015**, *1*, 14–27. [CrossRef]
35. García-González, J.; Lacek, J.; Retzer, K. Dissecting hierarchies between light, sugar and auxin action underpinning root and root hair growth. *Plants* **2021**, *10*, 111. [CrossRef] [PubMed]
36. Huang, G.; Zhang, D. The plasticity of root systems in response to external phosphate. *Int. J. Mol. Sci.* **2020**, *21*, 5955. [CrossRef] [PubMed]
37. Wang, L.; Li, X.; Mang, M.; Ludewig, U.; Shen, J. Heterogeneous nutrient supply promotes maize growth and phosphorus acquisition: Additive and compensatory effects of lateral roots and root hairs. *Ann. Bot.* **2021**, *128*, 431–440. [CrossRef] [PubMed]
38. Cabral, C.E.A.; Cabral, L.S.; Bonfim-Silva, E.M.; Carvalho, K.S.; Abreu, J.G.; Cabral, C.H.A. Reactive natural phosphate and nitrogen fertilizers in Marandu grass fertilization. *Comun. Sci.* **2018**, *9*, 729–736. [CrossRef]
39. Silva, C.T.R.; Bonfim-Silva, E.M.; Silva, T.J.A.; Pinheiro, E.A.R.; José, J.V.; Ferraz, A.P.F. Yield component responses of the *Brachiaria brizantha* forage grass to soil water availability in the brazilian Cerrado. *Agriculture* **2020**, *10*, 13. [CrossRef]
40. de Ollas, C.; Segarra, C.; Blázquez, M.A.; Agustí, J.; Gómez-Cadenas, A. Plant size directly correlates with water use efficiency in Arabidopsis. *Plant Cell Environ.* **2023**, *46*, 2711–2725. [CrossRef]
41. Hamidi, N.H.; Ahmed, O.H.; Omar, L.; Ch'ng, H.Y. Soil nitrogen sorption using charcoal and wood ash. *Agronomy* **2021**, *11*, 1801. [CrossRef]
42. Bonfim-Silva, E.M.; Fernandes, G.B.; Alves, R.D.S.; Castañon, T.H.F.M.; Silva, T.J.A. Mineral, organic and organomineral fertilization in rabanet culture. *Braz. J. Dev.* **2020**, *6*, 23300–23318. [CrossRef]
43. Hatfield, J.L.; Dold, C. Water-use efficiency: Advances and challenges in a changing climate. *Front. Plant Sci.* **2019**, *10*, 103. [CrossRef]
44. Li, X.; Farooqi, T.J.A.; Jiang, C.; Liu, S.; Sun, O.J. Spatiotemporal variations in productivity and water use efficiency across a temperate forest landscape of northeast China. *For. Ecosyst.* **2019**, *6*, 22. [CrossRef]

45. Cao, X.; Xiao, J.; Wu, M.; Zeng, W.; Huang, X. Agricultural water use efficiency and driving force assessment to improve regional productivity and effectiveness. *Water Res. Manag.* **2021**, *35*, 2519–2535. [CrossRef]
46. El-Nashar, W.; Elyamany, A. Adapting irrigation strategies to mitigate climate change impacts: A value engineering approach. *Water Res. Manag.* **2023**, *37*, 2369–2386. [CrossRef]