

Article

Organic Waste Mitigates the Negative Impacts Linked to Nutritional Starvation, Improving Soil Bioindicators, Defense System and Photosynthesis in Maize Plants

Maria Andressa Fernandes Gonçalves ¹, Lihua Chen ², Herdjanía Veras de Lima ¹,
Allan Klynger da Silva Lobato ¹ and Elaine Maria Silva Guedes Lobato ^{1,*}

¹ Programa de Pós-Graduação em Agronomia, Universidade Federal Rural da Amazônia, Rodovia PA 256, Paragominas 68.627-451, Pará, Brazil; agro.ufra.andressa@gmail.com (M.A.F.G.); herdjanía.lima@ufra.edu.br (H.V.d.L.); allan.lobato@ufra.edu.br (A.K.d.S.L.)

² College of Agricultural Science and Engineering, Hohai University, Nanjing 210000, China; chenlihua2001@163.com

* Correspondence: elaine.guedes@ufra.edu.br

Abstract

Sustainable agricultural technologies are essential to respond to environmental and social pressures, ensuring the maintenance of global food security. Therefore, there is an urgent demand for more sustainable agricultural practices that promote soil quality, as this factor directly impacts the global economy. Agricultural yield is directly associated with soil health and fertility. The use of organic waste serves as a source of essential nutrients for plants, increasing soil organic matter, contributing to the improvement of soil physical and chemical properties, as well as increasing crop yield. Based on this context, this research aimed to evaluate the effects of incorporating organic waste aiming to mitigate the oxidative damage in maize plants grown under different levels of soil fertility (low, average, and high), evaluating soil and plant, more specifically chemical, physiological, biochemical, and morphological responses. In soil, organic waste promoted significant increases in the activities of arylsulfatase and β -glucosidase and improved the chemical parameters, including cation exchange capacity, soil organic matter, base saturation, and sum of bases. The application of organic waste, regardless of fertility level, improved the nutritional status in maize plants, increased concentrations of photosynthetic pigments, maximized the photochemical efficiency and photosynthesis rate. In plant metabolism, the results demonstrated that organic waste promoted significant increases in plant antioxidant defense, including superoxide dismutase, catalase, ascorbate peroxidase, and peroxidase, minimizing the oxidative stress on photosynthetic machinery, especially in plants cultivated on soil with low fertility. Therefore, this research proves that organic waste mitigates the negative impacts associated with nutritional starvation, improves soil health and fertility, favors the maintenance of redox metabolism, and stimulates photosynthesis in maize plants cultivated in low-fertility soil.

Keywords: composting; nutritional status; photosynthetic process; redox metabolism; soil fertility



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1. Introduction

From the global socioeconomic panorama, the following emblematic one emerges: population growth and demand for food, becoming current challenges that directly confront

global agricultural systems [1]. It is estimated that by 2050 the global population will reach 9 billion people [2,3]. Thus, there is a correlation between food production and the high use of agrochemicals [4].

Maize (*Zea mays* L.) is classified as an annual plant belonging to the grass family Poaceae [5]. Corn cultivation has become widespread, becoming a crop of essential economic and social value and a source of high-yield cereals worldwide [6]. Its nutritional characteristics have allowed the crop to become part of the human diet and animal nutrition [7]. According to USDA estimates for the 2024/25 crop year, the United States produced approximately 377.6 million tons of corn, China about 295 million tons, and Brazil between 126 and 132 million tons, according to different official reports [8].

Fertilizers are certainly necessary in the agricultural production process [9]; however, the current principles of cultivation methods go beyond the need for nutrient replacement, because the production rates of plantations (crop yield per unit of land area) need to be enhanced to meet the demand for food [10] in this process to achieve the production objective. The intense use of fertilizers is used to increase the quantity and quality of the agricultural [11].

Excessive use of chemical fertilizers results in a series of [12], specifically related to soil damage [13], nutrient imbalance, organic matter losses, reduction in soil cation exchange capacity (CEC) [14], marked soil acidification [15], especially in tropical and subtropical regions, deterioration of soil structure due to disruption of soil aggregates, reducing the stability of soil particles and inferring damage to soil porosity and resulting in lower efficiency of fertilizer use [16]. There are significant losses of fertilizers, where these percentages vary between 40 and 70% of nitrogen, 80 and 90% of phosphorus and 50 and 70% of potassium, resulting in economic losses and environmental pollution [17].

The soil ecosystem is a complex environment, correlated with the interactions of biological, physical and chemical components, of which microorganisms play important roles in maintaining soil fertility and agricultural productivity [18]. Thus, the implementation of sustainable agricultural technologies is essential to respond to environmental and social pressures, ensuring the maintenance of global food security [19]. In this sense, there is an urgent demand for more sustainable agricultural practices that target soil quality, as this factor directly impacts the global economy [20]. Agricultural productivity rates are directly associated with soil health and fertility [21].

Organic waste can be utilized in the production of organic fertilizers [22]. The establishment and application of new organic waste-based products serve as a nutrient source and a relevant alternative to minimize the use of chemical fertilizers [23]. The reduction in input costs becomes possible through the application of organic waste, which is a possible technology for sustainable agricultural development [24].

Organic wastes composed by plant straw residues combined with food processing residues can be sources of nutrients and also increase the organic matter content of the soil [25]. Furthermore, benefits include increased crop yield, cation exchange capacity, base saturation, and the sum of bases of the soil [6], as well as greater stress tolerance and resistance to pathogens [24]. In addition, they contribute to ecological balance by favoring the development of soil microbial communities [26].

Research corroborates that the association between the application of chemical fertilizers with biofertilizers increases crop productivity rates by percentages ranging from 10% to 40%, in addition to representing reductions from 25% to 30% in the need for applications of chemical fertilizers [27,28]. Studies developed by several researchers in different countries obtained significant rates of reduction in the use of chemical fertilizers with the incorporation of organic waste or/and biofertilizers, obtaining a reduction of 25% in cultivating wheat [29], a 50% reduction in rice [30], and reduction of 50% in wheat crop [31].

In Brazil, research demonstrated that the use of biofertilizer in soybean cultivation can replace the need for chemical nitrogen fertilizers, without interfering with productivity rates and saving approximately US\$ 15 billion annually [32].

Given the scenario and the problem addressed, it is essential to study sustainable soil amendments [33]. Therefore, the hypothesis guiding this research is that the use of organic waste can reduce the problems caused by nutritional starvation during maize cultivation in degraded soils in the Amazon. In this context, this research aimed to evaluate effects promoted by organic waste in soil health and fertility, as well as antioxidant responses and physiological behavior in maize plants.

2. Results

2.1. Potential Properties Linked to Organic Waste

Organic waste has a neutral pH. The nitrogen (N), phosphorus (P), and potassium (K) values confirm the presence of these elements, and carbon/nitrogen (C/N) ratio with 27% and resistant organic matter at 26%, reflecting potential properties, being a waste that will persist longer in the soil and contribute to improving the chemical and, especially, physical structure of the soil.

2.2. Organic Waste Stimulated the Activities of Soil Enzymes

In soil with low fertility (Table 1), organic waste planting promoted significant increases in the activities of arylsulphatase (111%) and β -glucosidase (203%), compared to treatment with no fertilizer. Soil incorporated with organic waste topdressing boosted increases of 47% (arylsulphatase) and 266% (β -glucosidase). Mineral fertilizer resulted in increases in activities of arylsulphatase and β -glucosidase of 42% and 110%, respectively. Under average fertility (Table 1), organic waste planting increased 5% (arylsulphatase) and 4% (β -glucosidase). Organic waste topdressing maximized arylsulphatase (9%) and β -glucosidase (13%). The mineral fertilizer promoted increments in arylsulphatase (13%) and β -glucosidase (20%), respectively. Speaking of high-fertility conditions (Table 1), increases of 3% (arylsulphatase) and 12% (β -glucosidase) were found in organic waste planting, if compared to no fertilizer. Organic waste topdressing maximized arylsulphatase and β -glucosidase by 9% and 33%, respectively. Mineral fertilizer induced increases of 15% (arylsulphatase) and 24% (β -glucosidase).

Table 1. Activities of soil enzymes in maize plants grown at different soil fertility and treatments.

Fertility Soil	Treatment	Arylsulphatase ($\mu\text{g p-Nitrophenyl g}^{-1} \text{ h}^{-1}$)	β -Glucosidase ($\mu\text{g p-Nitrophenyl g}^{-1} \text{ h}^{-1}$)
Low	No fertilizer	26.5 $\pm$ 1.50 Cc	14.5 $\pm$ 0.5 Bc
Low	Organic waste—planting	56.0 $\pm$ 0.00 Ca	44.0 $\pm$ 1.0 Ba
Low	Organic waste—topdressing	39.0 $\pm$ 1.00 Cb	53.0 $\pm$ 1.0 Ba
Low	Mineral fertilizer—planting	37.5 $\pm$ 0.50 Cb	30.5 $\pm$ 1.5 Cb
Average	No fertilizer	52.5 $\pm$ 0.50 Ba	42.5 $\pm$ 0.5 Aa
Average	Organic waste—planting	28.5 $\pm$ 0.50 Bb	37.5 $\pm$ 0.5 Ba
Average	Organic waste—topdressing	55.0 $\pm$ 1.00 Ba	42.5 $\pm$ 0.5 Ca
Average	Mineral fertilizer—planting	57.0 $\pm$ 1.00 Ba	45.0 $\pm$ 0.0 Ba
High	No fertilizer	82.0 $\pm$ 2.00 Ac	50.5 $\pm$ 0.5 Ac
High	Organic waste—planting	84.5 $\pm$ 1.50 Abc	56.5 $\pm$ 1.5 Abc
High	Organic waste—topdressing	89.0 $\pm$ 1.00 Aab	67.0 $\pm$ 2.0 Aa
High	Mineral fertilizer—planting	94.0 $\pm$ 2.00 Aa	62.5 $\pm$ 1.5 Aab

Columns with different uppercase letters compare fertility soil (low, average, and high) and lowercase letters between treatments (no fertilizer, organic waste—planting, organic waste—topdressing, and mineral fertilizer—planting) indicate significant differences by Tukey's test ($p < 0.05$). Means $\pm$ SD, $n = 4$.

2.3. Chemical Properties of Soil Were Benefited by Organic Waste

Low soil fertility had improved the soil chemical properties (Table 2), detecting increments in cation exchange capacity (CEC), soil organic matter (SOM), base saturation

(V), and sum of bases (SBs) of 46%, 55%, 45%, and 112%, respectively. Organic waste topdressing maximized CEC, SOM, V, and SB by 39%, 53%, 57%, and 118%, sequentially. Mineral fertilizer application resulted in increases of 17% (CEC), 49% (SOM), 15% (V), and 5% (SB), compared to no-fertilizer treatment. In soil with average fertility (Table 2), organic waste planting maximized CEC, SOM, V, and SB by 2%, 35%, 27%, and 17%, respectively. Organic waste topdressing resulted in increases of 18% (CEC), 53% (SOM), 2% (V), and 10% (SB). Increases of 15% (CEC), 49% (SOM), 10% (V), and 16% (SB) were observed with mineral fertilizer, compared to the no-fertilizer treatment. Under conditions of high soil fertility (Table 2), organic waste planting induced increases of 21%, 64%, 9%, and 14% in CEC, SOM, V, and SB, in this order. Organic waste topdressing caused increases of 11%, 50%, 8%, and 6% in the variables CEC, SOM, V, and SB, respectively. Mineral fertilizer increased by 16%, 56%, 6%, and 1% in CEC, SOM, V, and SB, sequentially, compared to no-fertilizer treatment.

Table 2. Chemical attributes of soil under corn cultivation at different fertility levels and soil treatments.

Fertility Soil	Treatment	CEC (cmol _c dm ⁻³)	SOM (%)	V (%)	SB (cmol _c dm ⁻³)
Low	No fertilizer	5.48 ± 0.24 Cc	12.8 ± 0.25 Cb	39.7 ± 1.10 Cc	2.18 ± 0.15 Cb
Low	Organic waste—planting	8.03 ± 0.15 Ba	19.9 ± 0.55 Ca	57.7 ± 2.15 Cb	4.63 ± 0.16 Ca
Low	Organic waste—topdressing	7.63 ± 0.02 Aa	19.6 ± 0.30 Aa	62.3 ± 0.10 Ca	4.76 ± 0.02 Ba
Low	Mineral fertilizer—planting	6.44 ± 0.07 Bb	19.2 ± 0.30 Ba	45.6 ± 0.70 Bd	2.30 ± 0.70 Cb
Average	No fertilizer	5.77 ± 0.15 Ba	12.0 ± 0.05 Ba	69.0 ± 3.60 Bc	4.36 ± 0.29 Ba
Average	Organic waste—planting	5.91 ± 0.09 Cc	16.2 ± 0.25 Bb	87.8 ± 0.95 Aa	5.10 ± 0.03 Ba
Average	Organic waste—topdressing	6.81 ± 0.05 Bb	18.4 ± 1.45 Ba	70.4 ± 1.05 Bc	4.80 ± 0.07 Ba
Average	Mineral fertilizer—planting	6.63 ± 0.44 Bb	17.9 ± 0.70 Ba	76.0 ± 0.60 Ab	5.04 ± 0.37 Ba
High	No fertilizer	7.05 ± 0.01 Aa	15.4 ± 0.65 Aa	15.4 ± 0.65 Ab	6.40 ± 0.29 Aab
High	Organic waste—planting	8.54 ± 0.13 Ab	25.3 ± 0.40 Aa	25.3 ± 0.40 Ba	7.29 ± 0.52 Aa
High	Organic waste—topdressing	7.85 ± 0.04 Abc	23.2 ± 0.90 Aa	23.2 ± 0.90 Aa	6.81 ± 0.42 Ab
High	Mineral fertilizer—planting	8.17 ± 0.11 Ac	24.1 ± 3.10 Aa	24.1 ± 3.10 Aa	6.45 ± 0.18 Ab

CEC = cation exchange capacity; SOM = soil organic matter; V = base saturation; SB = sum of bases. Columns with different uppercase letters compare fertility soil (low, average, and high) and lowercase letters between treatments (no fertilizer, organic waste—planting, organic waste—topdressing, and mineral fertilizer—planting) indicate significant differences by Tukey's test ($p < 0.05$). Means ± SD, $n = 4$.

2.4. Photosynthetic Pigments Were Maximized After the Organic Waste Utilization

Plants in soil with low fertility presented significant reductions in photosynthetic pigments (Table 3). Better results were observed in the organic waste planting treatment, with increases of 187% in chlorophyll *a* (Chl *a*), 378% in chlorophyll *b* (Chl *b*), and 233% in total Chl (total Chl), compared to no-fertilizer treatment. The organic waste topdressing promoted increases of 158%, 250%, and 180% for Chl *a*, Chl *b*, and total Chl, respectively, while mineral fertilizer induced increases of 64% (Chl *a*), 73% (Chl *b*), and 66% (total Chl), compared with treatment without fertilizer. Speaking of average fertility (Table 3), the treatment using organic waste topdressing had the highest concentrations of Chl *a*, Chl *b*, and total Chl, with increases of 130%, 176%, and 143%, respectively, compared to no fertilizer. The organic waste planting also presented significant increases of 110% (Chl *a*), 107% (Chl *b*), and 109% (total Chl). Mineral fertilizer resulted in increases of 79% (Chl *a*), 30% (Chl *b*) and 66% (total Chl). Under high fertility (Table 3), increases in photosynthetic pigments were observed. The organic waste topdressing treatment resulted in increments of 44%, 74%, and 49% for Chl *a*, Chl *b*, and total Chl, respectively, compared to no-fertilizer treatment. The organic waste planting treatment resulted in maximizations of 22% (Chl *a*), 51% (Chl *b*), and 27% (total Chl). Mineral fertilizer promoted significant increases of 58% (Chl *a*), 82% (Chl *b*), and 62% (total Chl), if compared to no-fertilizer treatment.

Table 3. Photosynthetic pigments in maize plants grown at different soil fertility and treatments.

Fertility Soil	Treatment	Chl <i>a</i> (mg g ⁻¹ FM)	Chl <i>b</i> (mg g ⁻¹ FM)	Total Chl (mg g ⁻¹ FM)	Car (mg g ⁻¹ FM)	Ratio Chl <i>a</i> /Chl <i>b</i>	Ratio Total Chl/Car
Low	No fertilizer	1.25 ± 0.01 Cd	0.40 ± 0.03 Bc	1.65 ± 0.03 Cd	0.48 ± 0.12 Bb	3.14 ± 0.24 Ba	3.61 ± 0.81 Ba
Low	Organic waste—planting	3.60 ± 0.11 Ba	1.91 ± 0.17 Aa	5.50 ± 0.17 Ca	1.05 ± 0.26 Ab	1.90 ± 0.24 Cb	5.44 ± 1.22 Ab
Low	Organic waste—topdressing	3.22 ± 0.18 Cb	1.40 ± 0.25 Bb	4.62 ± 0.07 Cb	0.54 ± 0.15 Bb	2.40 ± 0.50 Bab	9.05 ± 2.48 Bb
Low	Mineral fertilizer—planting	2.05 ± 0.07 Cc	0.69 ± 0.10 Cc	2.74 ± 0.10 Cc	0.73 ± 0.05 Cab	3.02 ± 0.45 Ba	3.76 ± 0.17 ABb
Average	No fertilizer	2.57 ± 0.03 Bd	0.98 ± 0.10 Ad	3.55 ± 0.10 Bd	0.73 ± 0.04 Abc	2.62 ± 0.16 Bb	8.61 ± 0.30 Bbc
Average	Organic waste—planting	5.40 ± 0.17 Ab	2.03 ± 0.03 Ab	7.43 ± 0.16 Ab	1.31 ± 0.13 Ab	2.65 ± 0.11 Bb	5.69 ± 0.54 Ab
Average	Organic waste—topdressing	5.91 ± 0.08 Ba	2.71 ± 0.20 Aa	8.62 ± 0.15 Aa	1.54 ± 0.03 Bc	2.19 ± 0.18 Bb	5.61 ± 0.21 Aa
Average	Mineral fertilizer—planting	4.61 ± 0.19 Bc	1.28 ± 0.07 Bc	5.89 ± 0.24 Bc	2.69 ± 0.20 Aa	3.61 ± 0.13 ABa	2.19 ± 0.08 Bc
High	No fertilizer	4.59 ± 0.11 Ad	0.95 ± 0.07 Ac	5.54 ± 0.12 Ad	0.99 ± 0.21 Ab	4.87 ± 0.37 Aa	4.19 ± 0.14 Aa
High	Organic waste—planting	5.59 ± 0.25 Ac	1.43 ± 0.09 Bb	7.02 ± 0.16 Bc	1.21 ± 0.09 Ab	3.92 ± 0.41 Ab	5.84 ± 0.37 Aa
High	Organic waste—topdressing	6.62 ± 0.04 Ab	1.65 ± 0.13 Bab	8.27 ± 0.11 Bb	1.94 ± 0.08 Aa	4.04 ± 0.33 Ab	4.28 ± 0.24 Ca
High	Mineral fertilizer—planting	7.26 ± 0.17 Aa	1.72 ± 0.17 Aa	8.98 ± 0.00 Aa	1.76 ± 0.36 Ba	4.24 ± 0.51 Aab	5.09 ± 0.09 Aa

Chl *a* = chlorophyll *a*; Chl *b* = chlorophyll *b*; total chl = total chlorophyll; car = carotenoids. Columns with different uppercase letters compare fertility soil (low, average, and high) and lowercase letters between treatments (no fertilizer, organic waste—planting, organic waste—topdressing, and mineral fertilizer—planting) indicate significant differences by Tukey's test ($p < 0.05$). Means ± SD, $n = 4$.

2.5. Gas Exchange Was Improved After Organic Waste Utilization

Plants grown under low soil fertility levels showed significant decreases in gas exchange (Table 4). However, the incorporation of organic waste in maize plant cultivation promoted benefits to the photosynthetic machinery. The treatment with organic waste planting resulted in increases of 14%, 29%, 25%, and 103%, and a decrease in 43% and 9%, respectively, in net photosynthetic rate (P_N), stomatal conductance (g_s), water-use efficiency (WUE), carboxylation instantaneous efficiency (P_N/C_i), intercellular CO₂ concentration (C_i), and transpiration rate (E), compared to no-fertilizer treatment. Waste organic topdressing provided increases in g_s (32%), P_N (4%), WUE (14%), P_N/C_i (61%), and reductions in C_i (35%) and E (8%). The mineral fertilizer inferred increases in g_s (4%), P_N (4%), WUE (3%), P_N/C_i (35%) and decreases in C_i (23%) and E (1%). Speaking of plants grown under average fertility (Table 4), organic waste planting promoted increases in g_s , P_N , WUE, and P_N/C_i of 43%, 8%, 14% and 22%, respectively, and reductions of 12% and 5% in C_i and E , respectively, when compared to no-fertilizer treatment. Organic waste topdressing treatment resulted in increases in g_s (52%), P_N (12%), WUE (25%), and P_N/C_i (37%), and reductions in C_i (18%) and E (10%). Mineral fertilizer promoted increases in g_s (10%), P_N (4%), WUE (10%) and P_N/C_i (15%) and reductions in C_i (10%) and E (6%). Under high soil fertility conditions (Table 4), the treatment with organic waste planting promoted increases of 12%, 6%, 8%, and 21% in g_s , P_N , WUE, and P_N/C_i , respectively, with a decrease in C_i of 12%, when compared to no-fertilizer treatment. Organic waste topdressing promoted increases of 12% (g_s), 8% (P_N), 11% (WUE), 31% (P_N/C_i), and reductions of 16% (C_i) and 3% (E). Mineral fertilizer resulted in increases of 24% (g_s), 9% (P_N), 13% (WUE), 33% (P_N/C_i), and reductions of 18% (C_i) and 4% (E).

Table 4. Gas exchange in maize plants grown at different soil fertility and treatments.

Fertility Soil	Treatment	P_N ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	E ($\text{mmol m}^{-2} \text{s}^{-1}$)	g_s ($\text{mol m}^{-2} \text{s}^{-1}$)	C_i ($\mu\text{mol mol}^{-1}$)	WUE ($\mu\text{mol mmol}^{-1}$)	P_N/C_i ($\mu\text{mol m}^{-2} \text{s}^{-1} \text{Pa}^{-1}$)
Low	No fertilizer	20.30 $\pm$ 0.30 Bb	1.47 $\pm$ 0.02 Ba	0.09 $\pm$ 0.01 Aa	130 $\pm$ 2.08 Aa	13.80 $\pm$ 0.40 Ac	0.16 $\pm$ 0.01 Ac
Low	Organic waste—planting	23.10 $\pm$ 0.50 ABa	1.34 $\pm$ 0.06 Bab	0.12 $\pm$ 0.03 Bc	74 $\pm$ 10.79 Bc	17.20 $\pm$ 1.00 Aa	0.30 $\pm$ 0.01 Aa
Low	Organic waste—topdressing	21.20 $\pm$ 0.40 Bb	1.35 $\pm$ 0.04 Bb	0.12 $\pm$ 0.06 Bc	85 $\pm$ 4.51 Bc	15.70 $\pm$ 0.20 Bb	0.30 $\pm$ 0.01 Ab
Low	Mineral fertilizer—planting	21.10 $\pm$ 0.40 Bb	1.49 $\pm$ 0.08 Bab	0.10 $\pm$ 0.01 Ab	101 $\pm$ 1.15 Ab	14.20 $\pm$ 0.80 Bc	0.21 $\pm$ 0.02 Ab
Average	No fertilizer	21.10 $\pm$ 0.10 Bc	1.45 $\pm$ 0.02 Ba	0.07 $\pm$ 0.01 Ba	113 $\pm$ 2.65 Ba	14.60 $\pm$ 0.20 Ac	0.19 $\pm$ 0.00 Ab
Average	Organic waste—planting	22.70 $\pm$ 0.30 Bab	1.37 $\pm$ 0.10 Bab	0.10 $\pm$ 0.01 Aab	99 $\pm$ 4.04 bAab	16.60 $\pm$ 1.40 ABb	0.23 $\pm$ 0.01 Bab
Average	Organic waste—topdressing	23.70 $\pm$ 0.30 Aa	1.30 $\pm$ 0.05 Bb	0.11 $\pm$ 0.01 ABb	93 $\pm$ 3.06 ABb	18.20 $\pm$ 0.90 Aa	0.26 $\pm$ 0.01 Aa
Average	Mineral fertilizer—planting	21.90 $\pm$ 0.80 Bbc	1.37 $\pm$ 0.08 Bab	0.08 $\pm$ 0.02 Aab	102 $\pm$ 2.08 Aab	16.00 $\pm$ 0.30 Abc	0.22 $\pm$ 0.01 Aab
High	No fertilizer	22.70 $\pm$ 0.50 Ab	1.58 $\pm$ 0.10 Aa	0.14 $\pm$ 0.06 ABa	122 $\pm$ 2.60 ABa	14.40 $\pm$ 0.30 Ab	0.19 $\pm$ 0.01 Ab
High	Organic waste—planting	24.20 $\pm$ 0.30 Aa	1.56 $\pm$ 0.03 Aab	0.15 $\pm$ 0.01 Aab	108 $\pm$ 10.20 Aab	15.50 $\pm$ 0.30 Bab	0.23 $\pm$ 0.03 Bab
High	Organic waste—topdressing	24.60 $\pm$ 1.30 Aa	1.54 $\pm$ 0.07 Bb	0.15 $\pm$ 0.01 Ab	103 $\pm$ 15.10 Ab	16.00 $\pm$ 0.90 Ba	0.24 $\pm$ 0.04 Aa
High	Mineral fertilizer—planting	24.70 $\pm$ 0.60 Aa	1.52 $\pm$ 0.07 Bab	0.17 $\pm$ 0.05 Ab	100 $\pm$ 4.00 Ab	16.20 $\pm$ 0.40 Aa	0.25 $\pm$ 0.02 Aa

P_N = net photosynthetic rate; E = transpiration rate; g_s = stomatal conductance; C_i = intercellular CO_2 concentration; WUE = water-use efficiency; P_N/C_i = carboxylation instantaneous efficiency. Columns with different uppercase letters compare fertility soil (low, average, and high) and lowercase letters between treatments (no fertilizer, organic waste—planting, organic waste—topdressing, and mineral fertilizer—planting) indicate significant differences by Tukey's test ($p < 0.05$). Means $\pm$ SD, $n = 4$.

2.6. Plant Defense System Was Boosted by Organic Waste

Under low-fertility conditions (Figure 1), the antioxidant enzymes ascorbate peroxidase (APX), catalase (CAT), peroxidase (POX), and superoxide dismutase (SOD) exhibited significant increases in activities; maize plants treated with organic waste planting resulted in sequential increases of 80%, 53%, 543%, and 50%, respectively, compared with treatment without fertilizer. The organic waste topdressing treatment promoted significant increases of 30% (APX), 22% (CAT), 409% (POX), and 35% (SOD). Mineral fertilizer promoted increases of 19% (APX), 17% (CAT), 45% (POX), and 23% (SOD). In plants cultivated in soil with average fertility (Figure 1), organic waste planting presented increments in APX, CAT, POX, and SOD of 46%, 222%, 60%, and 68%, sequentially, compared to no-fertilizer treatment. Subsequently, the organic waste topdressing treatment promoted significant increases of 100% (APX), 446% (CAT), 182% (POX), and 107% (SOD). The mineral fertilizer had increases of 8% (APX), 133% (CAT), 36% (POX), and 39% (SOD). Under high soil fertility conditions (Figure 1), organic waste planting treatment promoted increases of 16%, 9%, 6%, and 43% in APX, CAT, POX, and SOD, respectively, when compared to no-fertilizer treatment. The organic waste topdressing treatment induced increases in enzymes APX (135%), CAT (49%), POX (48%), and SOD (68%). Mineral fertilizer resulted in increases of 210% (APX), 74% (CAT), 77% (POX), and 80% (SOD).

2.7. Organic Waste Incorporated in Soil Attenuated Oxidative Stress in Plants

To oxidative stress indicators (Figure 2), specifically reactive oxygen species, including hydrogen peroxide (H_2O_2) and superoxide (O_2^-) and membrane damage, such as malondialdehyde (MDA) and electrolyte leakage (EL) in maize plants subjected to nutritional deficiency, showed significant increases in these compounds. However, treatments with organic waste in low-fertility soil promoted substantial reductions. The treatment with organic waste planting resulted in decreases of 30%, 19%, 37%, and 49% for EL, MDA, H_2O_2 , and O_2^- , respectively, compared to no-fertilizer treatment. Organic waste topdressing promoted reductions of 28% (EL), 25% (MDA), 18% (H_2O_2), and 48% (O_2^-). The treatment with mineral fertilizer also induced decreases of 18% (EL), 4% (MDA), 6% (H_2O_2), and 36% (O_2^-). In soil with average fertility (Figure 2), organic waste planting promoted decreases

in EL, MDA, H_2O_2 , and O_2^- of 30%, 43%, 19%, and 42%, respectively, compared with no-fertilizer treatment. The organic waste topdressing treatment resulted in reductions of 38% (EL), 47% (MDA), 24% (H_2O_2), and 47% (O_2^-). Mineral fertilizer also promoted reductions in oxidative stress with reductions of 29%, 35%, 11%, and 5% in EL, MDA, H_2O_2 , and O_2^- , respectively. Under high-fertility conditions (Figure 2), the treatments continued to favor the reduction in oxidative stress. The organic waste planting treatment promoted reductions of 9% (EL), 33% (MDA), 24% (H_2O_2), and 29% (O_2^-) when compared to no-fertilizer treatment. Organic waste topdressing promoted decreases of 37%, 36%, 25%, and 33% in EL, MDA, H_2O_2 , and O_2^- , respectively. Mineral fertilizer expressed reductions of 38% in EL, 39% in MDA, 27% in H_2O_2 , and 63% in O_2^- , respectively.

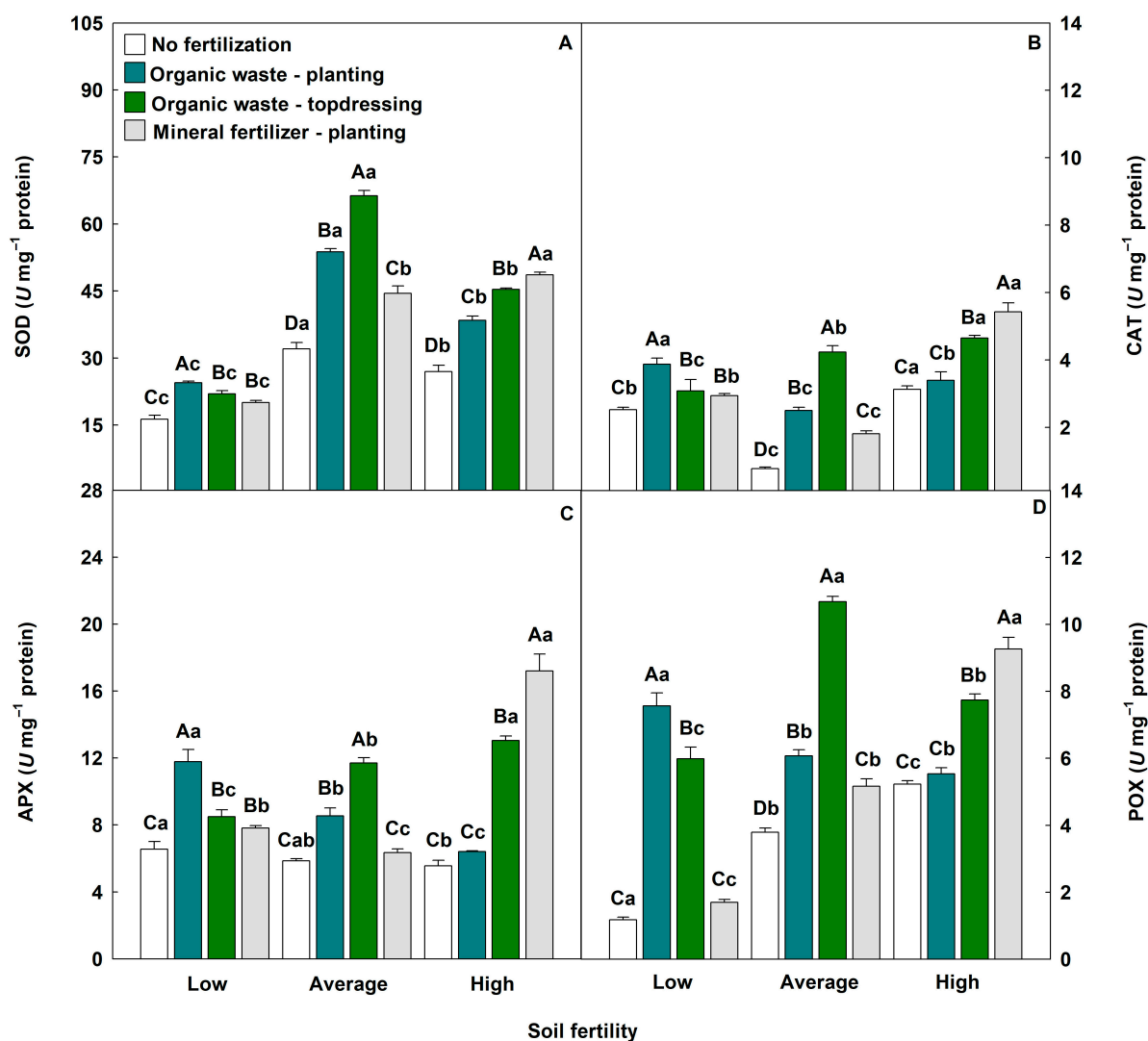


Figure 1. Activities of superoxide dismutase (SOD; (A)), catalase (CAT; (B)), ascorbate peroxidase (APX; (C)) and peroxidase (POX; (D)) in maize plants grown at different soil fertility and treatments. Columns with different uppercase letters compare fertility soil (low, average, and high) and lowercase letters between treatments (no fertilizer, organic waste—planting, organic waste—topdressing, and mineral fertilizer—planting) indicate significant differences by Tukey's test ($p < 0.05$). Means $\pm$ SD, $n = 4$.

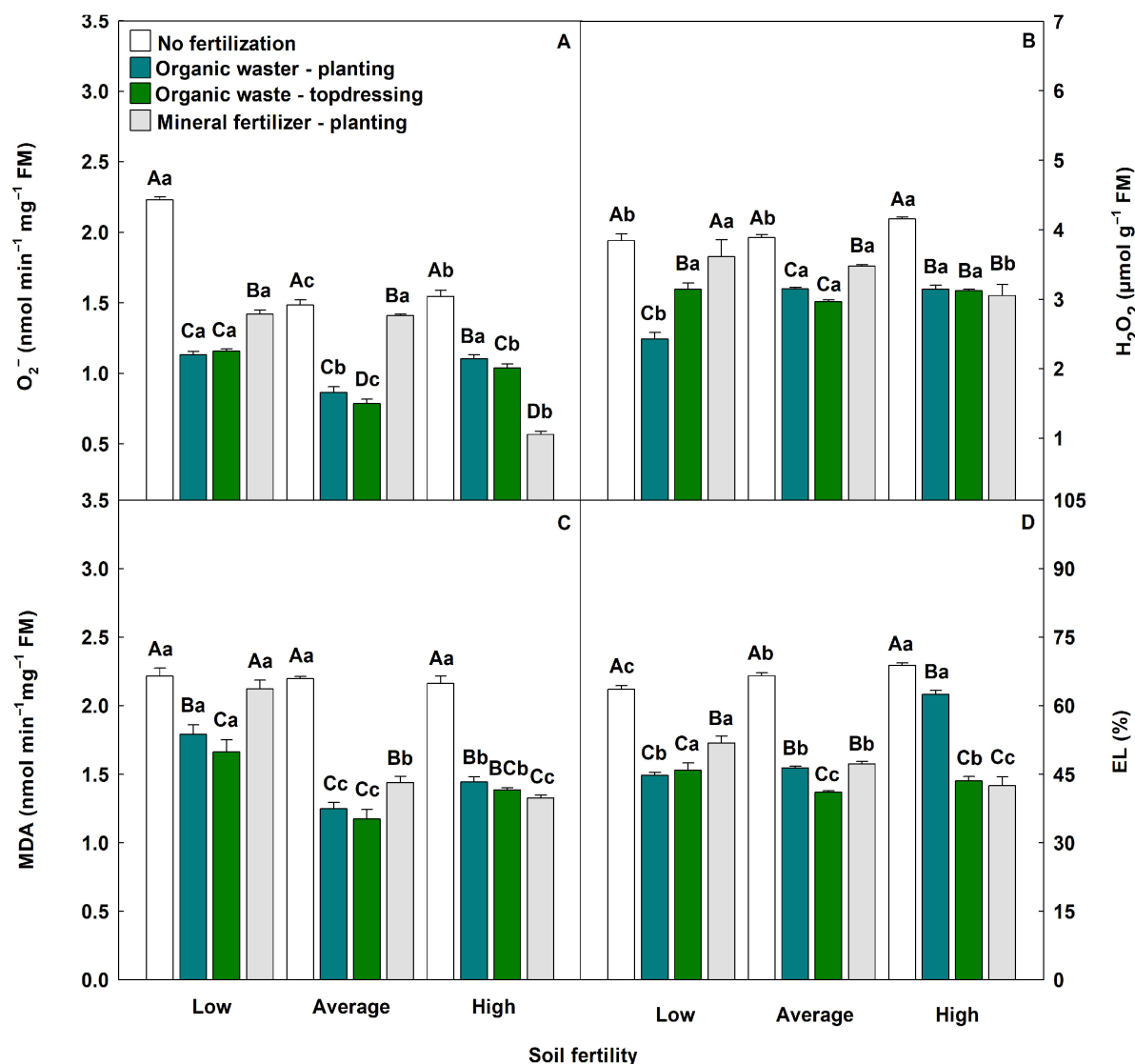


Figure 2. Superoxide (O_2^- ; (A)), hydrogen peroxide (H_2O_2 ; (B)), malondialdehyde (MDA; (C)) and electrolyte leakage (EL; (D)) in maize plants grown at different soil fertility and treatments. Columns with different uppercase letters compare fertility soil (low, average, and high) and lowercase letters between treatments (no fertilizer, organic waste—planting, organic waste—topdressing, and mineral fertilizer—planting) indicate significant differences by Tukey's test ($p < 0.05$). Means $\pm$ SD, $n = 4$.

2.8. Biomass and Growth Were Positively Modulated by Organic Waste

Biomass was affected by nutritional deficiency in maize plants. However, the incorporation of organic waste reduced the deleterious effects. In low soil fertility (Figure 3), organic waste planting resulted in increases of 171%, 50%, 50% and 115% in shoot dry matter (SDM), plant height (PH), root collar diameter (RCD), and first spike height (FSH), respectively, compared to no-fertilizer treatment. Organic waste topdressing produced increments of 141% (SDM), 56% (PH), 55% (RCD), and 141% (FSH). Mineral fertilizer had increases of 106%, 40%, 40%, and 93% in SDM, PH, RCD and FSH, sequentially. With average fertility (Figure 3), incorporating organic waste planting values of SDM, PH, RCD and FSH increased by 142%, 30%, 30% and 52%, sequentially, compared to treatment with no fertilizer. Organic waste topdressing resulted in increases of 129% (SDM), 50% (PH), 50% (RCD), and 63% (FSH). Mineral fertilizer promoted significant responses in biomass, resulting in increments of 152% (SDM), 53% (PH), 55% (RCD), and 43% (FSH). Under high fertility (Figure 3), the supply of organic waste planting induced significant increases in

SDM (69%), PH (53%), RCD (54%), and FSH (34%). Organic waste topdressing promoted increments of 95%, 51%, 61% and 35% in SDM, PH, RCD, and FSH, in this order. Mineral fertilizer increased by 31%, 54%, 64% and 31% in SDM, PH, RCD, and FSH, respectively.

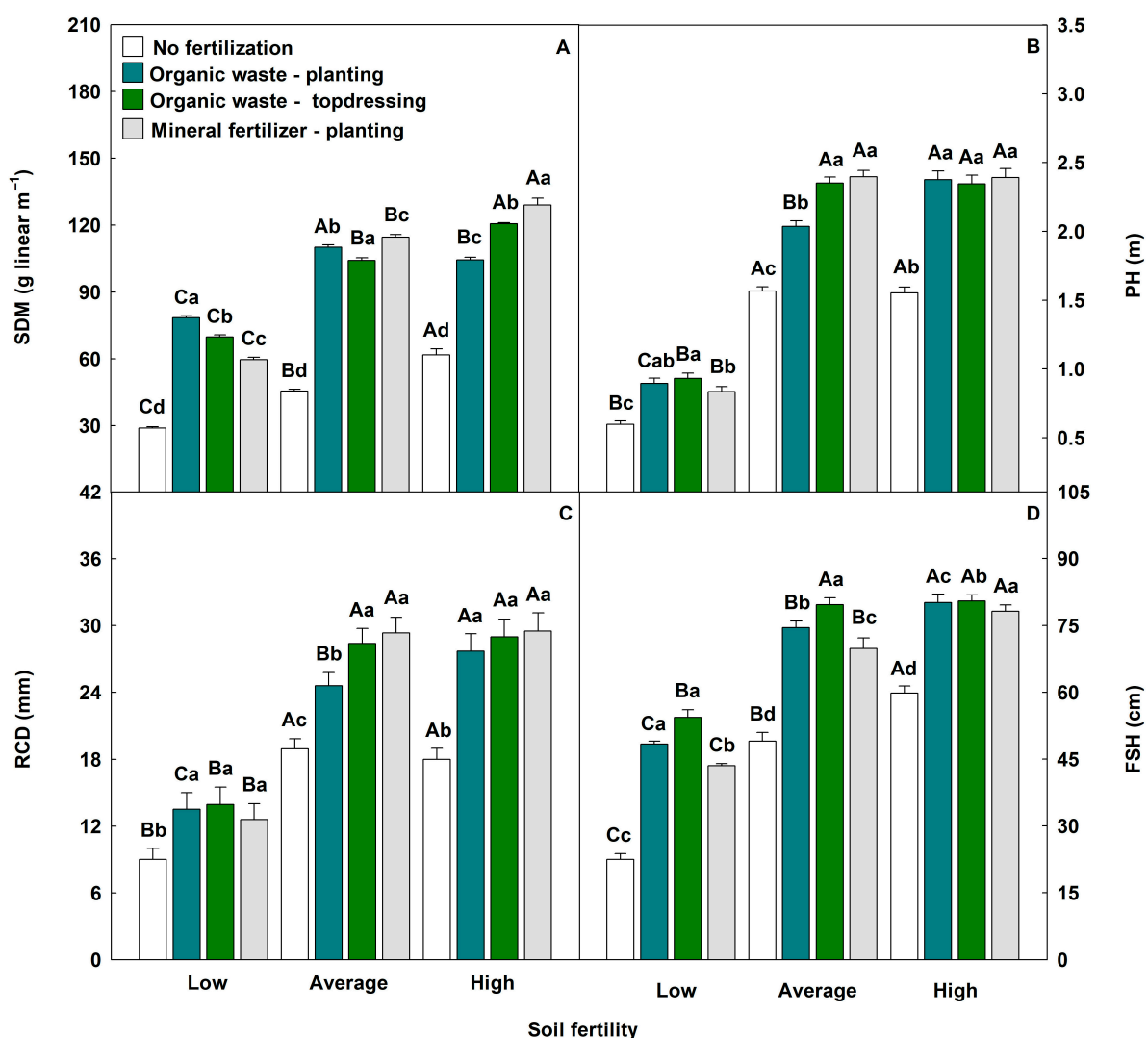


Figure 3. Shoot dry matter (SDM; (A)); plant height (PH; (B)); root collar diameter (RCD; (C)) and FSH (first spike height; (D)) in maize plants grown at different soil fertility and treatments. Columns with different uppercase letters compare fertility soil (low, average, and high) and lowercase letters between treatments (no fertilizer, organic waste—planting, organic waste—topdressing, and mineral fertilizer—planting) indicate significant differences by Tukey's test ($p < 0.05$). Means $\pm$ SD, $n = 4$.

3. Discussion

Overall, this research reported the effect of organic waste on different soil fertility levels, improving the nutritional status of maize plants. Disturbances in plant metabolism were minimized, especially at low-fertility levels, resulting in benefits on biochemical, physiological, and morphological aspects. Potential properties linked to organic waste were confirmed benefits that promoted on chemical parameters of the soil, including cation exchange capacity, soil organic matter, base saturation, and sum of bases; these effects occurred probably due to transformation of organic compounds to induce long-chain aromatic compounds, such as polyphenols and lignins [34]. Particulate organic C plays a fundamental role, acting as a bridge for C stabilization and providing greater longevity

for intra-aggregate carbon. This fraction delivers more resistant compounds to the soil, aromatized and associated with clay and silt minerals.

Soil enzymes selected for this study were β -glucosidase and arylsulfatase, being biological indicators of soil quality, and four indicators related to chemical properties (OM, CEC, SB, and V%), because they are components of soil analysis. In all research evaluated, which was categorized as low, average, and high fertility, increases in the activity of the enzymes arylsulphatase and β -glucosidase were observed after maize cultivation, promoted by organic waste. These enzymes serve as indicators of soil quality, due to their sensitivity and fast response to changes in soil management [35,36]. Soil enzymatic activity contributes to soil biological health, representing an essential ecological characteristic [37]. The contribution of organic waste through the transformation of organic matter, distribution, and carbon mining is due to the activity of the enzyme β -glucosidase, which is linked to the phosphorus cycle [38]. Arylsulphatase is directly linked to the soil sulfur cycle, indicating increased soil sulfur availability in the form of sulfate [38]. In general, enzymes play fundamental roles in the biological process, whose nutrient supply and catalytic reactions depend on their activity [39], serving to evaluate the microbial activity in soil, detecting changes in environment, and being directly affected by organic matter [40]. Application of an organic waste combined with phosphorus and beneficial bacterial strains improved the microbiological parameters of degraded soil, including soil enzymatic activity, enzyme β -glucosidase, and genetic and functional diversity of the soil microbiome in maize plants, where they obtained increases in crop yield [41]. The research aims to reduce chemical fertilization and improve the sustainability of common wheat cultivation. It introduced three organic wastes into the cultivation system and found increases in rhizosphere microbial biomass and the activity of enzymes, such as β -glucosidase [42]. Positive effects were found in the association of organic waste and biofertilizer in the cultivation of *Juglans regia*, where they inferred an increase in crop yields, as well as direct benefits in soil quality, where the authors use an index called SQI; this index integrates the physical-chemical and microbiological properties of the soil [43].

The incorporation of organic waste into clayey soil, specifically across all fertility levels evaluated in this study, increased soil organic matter (SOM) content, which is associated with the benefits provided by enzymes β -glucosidase and arylsulfatase, as confirmed by the SDM obtained in this study. Frequently, there is a correlation between SOM and pH, where these two factors positively drive soil enzymatic activity [44]. SOM participates in multifaceted physical, chemical, and biological processes of the soil microenvironment [45], including the soil composition itself, that is, chemical and physical characteristics, including pH, CEC, color, and element sorption and water retention properties [46]. Thus, SOM levels have a direct effect on soil fertility levels, as well as on the availability of nutrients, such as nitrogen and phosphorus, which contribute to agricultural yield [47]. Maize plants were cultivated with organic waste application and obtained promising results in soil assessments, highlighting increases in soil organic matter content (60.9%), increases in total soil nitrogen levels (60.5%), as well as dissolved organic carbon (52.2%), and increases in plant biomass [48]. Management strategy in maize plants intends to replace 50% of the urea application rate with organic fertilizer, where the researchers found a 54% reduction in nitrogen loss from agricultural land. The organic fertilizer increased SOM content, organic nitrogen, yield, and improved soil structure [49].

Clayey soil fertility parameters improved after organic waste application in maize cultivation in all study areas with different soil fertility (low, average, and high). The organic waste improved all main fertility indexes, particularly CEC, SB, and V%. Cation exchange capacity (CEC), sum of bases (SBs), and base saturation (V%) are soil properties used to describe fertility-related indicators [50]. CEC is the mechanism capable of storing

and making available macro- and micronutrients to plants [51]. Specifically, negatively charged clay particles can bind positively charged elements, such as Ca, Mg, K, Cu, Zn, and Fe [52]. Other soil structures are influenced by CEC, such as soil buffering, soil structure stability, pH, and fertilizer response [53]. SB and V% levels are directly associated with crop growth and yield; therefore, maintaining adequate levels benefits soil health and agricultural production [54]. The exchangeable cations (SB), including Ca, Mg, and K, are essential nutrients for the proper plant development and microbial metabolism [55]. Samijan et al., (2024) [56] applied organic fertilizer to the soil, where they evaluated the soil chemistry in the sorghum crop, improving the CEC values and revealing increases in CEC and nutrient availability.

Organic waste provided significant increases in chloroplastic pigments, being associated with increases in nutrient concentrations, including Mg. During the photosynthetic process, the main pigment is chlorophyll, responsible for capturing and converting light energy in the leaves, within the photosynthetic apparatus [57]. Chlorophyll content is correlated with growth, biomass, and nutritional status [58,59]. In higher plants, chlorophyll is a complex molecule consisting of a porphyrin ring centered on Mg^{2+} and chlorophyll alcohols [60]. Positive responses in the cultivation of *Trigonella foenum-graecum* plants with organic fertilizer promote significant increases in chlorophyll concentrations [61]. Benefits linked to the utilization of organic fertilizers in potato plants under the reduction in water—nitrogen (N), phosphorus (P), and potassium (K) fertilizers—increased root dry matter, shoot dry matter, leaf area, water saturation deficit, and chlorophyll index [62]. A combination of organic fertilizer and bacteria in *Brassica juncea* plants induced significant increases in chlorophyll and carotenoid contents, even under drought conditions [63].

Increases in gas exchange were associated with the use of organic waste in maize cultivation, increasing g_s and P_N . This was also associated with a positive effect on nutrient bioavailability. Nutritional management is crucial for healthy plant growth and development. Notably, the following three macronutrients are essential in the photosynthetic process: N, P, and K [64]. K positively influences stomatal function and biomass production, plays a key role in photoassimilate production, and increases P_N [65,66]. There is a correlation between P application and increased P_N rates, also increasing chlorophyll biosynthesis and influencing improvements in chloroplast ultrastructure and stomatal opening. P also enhances antioxidant defense mechanisms in plants under stressful conditions [67]. Stomatal density and stomatal functionality were probably enhanced, which benefits CO_2 capture and distribution in the leaves through the stomatal opening of the leaf, serving as a leading indicator of CO_2 influx and water vapor efflux [68]. This is confirmed by the benefits observed in g_s and the reductions in C_i . In agreement with our study, organic fertilizer mixed with plant growth-promoting rhizobacteria presented effectiveness in improving tolerance to nutritional deficit in strawberry plants, benefiting gas exchange, including g_s and P_N [69]. Biofertilization with plant growth-promoting rhizobacteria and arbuscular mycorrhizal fungi observed a positive effect on gas exchange in the leaves of pepper plants, improving growth, P content, and gas exchange (C_i , E , g_s , and P_N) [70].

Activities of the antioxidant enzymes (SOD, CAT, APX, and POX) were improved by the incorporation of organic waste, promoting detoxification and reducing the accumulation of reactive oxygen species (ROS) [71], caused by adverse conditions, such as nutritional deficiency [72]. Environmental factors can cause stress to plants, including nutrition and water. Under these conditions, plant metabolism produces high levels of ROS, causing oxidative damage to DNA, RNA, proteins, and lipids [73]. Plants develop a protective mechanism involving enzymes that act to eliminate ROS [74,75]. Among them, APX has an affinity for H_2O_2 , catalyzing its reduction to water and utilizing ascorbate as an electron

donor in various subcellular compartments [76]. Likewise, the enzymes POX, SOD, and CAT favor the development process of plant metabolism [77].

Our study found a reduction in H_2O_2 and an increase in ETR in maize plants grown with the presence of organic waste at three soil fertility levels. Corroborating this study, promising responses in the use of organic fertilizer combined with reduced chemical fertilization improved the growth, nutritional status, and antioxidant defense of *E. guineensis* grown in low soil fertility [78]. Organic fertilizer improved the tolerance of rice plants against oxidative stress, decreasing MDA and increasing antioxidant enzymes, and increasing nitrogen, phosphorus, and potassium contents, when compared to the control treatment [79].

The incorporation of organic waste into maize cultivation resulted in significant decreases in O_2^- and H_2O_2 concentrations, attributed to the efficient functioning of the antioxidant system, stimulated by increases in the activities of the enzymes SOD, CAT, APX, and POX, following reductions in MDA and EL. ROS molecules, such as O_2^- , H_2O_2 , MDA, and EL, are excessively produced under stress conditions [80]. Oxidative stress is characterized by high levels of lipid oxidation in the cell membrane, resulting in a considerable increase in MDA levels [81]. Oxidative stress results from an imbalance between ROS production and natural cell detoxification [82]. This imbalance severely damages cellular components such as DNA, proteins, and carbohydrates and can lead to cell death [83]. Corroborating our study, *Calendula officinalis* plants incorporated with organic fertilizers during drought stress presented increases in chlorophyll, carotenoid, membrane stability, CAT and APX levels, while decreasing EL and MDA levels, compared to the control treatment [84].

The incorporation of organic waste into maize cultivation reduced the deleterious effects on biomass (SDM, RCD, FSH, and PH) caused by nutritional deficiency at different soil fertility levels. This fact can be explained by the benefits to nutritional status and antioxidant system, combined with increases in photosynthetic pigments and gas exchange, positively modulating growth and development. The incorporation of organic waste into the growing medium prevents nutrient loss through leaching, directly favoring the supply of nutrients necessary for plant growth [85]. This increases the uptake capacity of these nutrients, favoring root development and leading to improved photosynthetic efficiency [86]. Results obtained in this research corroborate the positive effects of organic fertilizer on okra plants under water deficit, resulting in increases in shoot dry matter, root dry matter, plant height, and leaf area [87]. Water stress in maize plants was attenuated through the incorporation of organic fertilizer, resulting in increased shoot dry weight, plant height, chlorophyll, nitrogen, phosphorus, and iron concentrations, compared to the control [88].

4. Materials and Methods

4.1. Location and Soil

The research was carried out at the experimental area from COOPERNORTE, Paragominas, Brazil ($2^\circ 57' \text{ S}$, $47^\circ 26' \text{ W}$). The soil in the experimental areas was classified as Yellow Latosol and had the following three fertility levels: low, medium, and high. According to Köppen, the climate is of type “Af,” characterized as hot and humid.

4.2. Experimental Design

The experimental design consisted of completely randomized blocks, main plot with three soil fertility levels (low, average, and high) and subplots with four treatments (no fertilizer, organic waste—planting, organic waste—topdressing, and mineral fertilizer—

planting). This study consisted of four blocks, totaling 48 experimental plots. Each plot was 15 m², with seven rows of 5 m each and 0.5 m between rows.

4.3. Organic Waste, Soil Fertility, and Agricultural Areas

Organic waste was composed of plant straw residues (corn, sorghum, and peanuts), combined with food processing residues (bran cake, soybean meal, sweepings extraction, and rice bran). The production process was carried out using a fully enclosed storage tank, automatic tumbling, with phases of biological deodorization and high-temperature aerobic fermentation with antibiotic release, ensuring the complete elimination of pests and helminths, being confirmed by parasitological analysis. The chemical characterization of organic waste is presented in Table 5. The agricultural areas were defined for this research as low, average, and high fertility, based on chemical and physical characteristics (Tables 6 and 7). The high-fertility area had soybean and grass planted in previous years, with limestone (2.5 tons.ha⁻¹) applied to the surface in the 2023/2024 agricultural year. The average-fertility area had no grass planting, only limestone application (2.5 tons.ha⁻¹) and soil turnover to 0.20 m, and the low-fertility area had no previous cultivation or soil amendment. All areas are classified as very clayey with a 1:1 activity (Table 7).

Table 5. Chemical characterization of organic waste.

pH CaCl	Moisture	OM Total	OM Compostable	OM Resistant	Total Carbon	C/N Ratio	C/N Ratio (C Organic)	N Total	P (P ₂ O ₅ Total)	K (K ₂ O)
7.24	34.05	38.41	12.23	26.18	22.33	27	8	0.84	2.38	2.64
Ca	Mg	S	B	Fe	Mn	Zn	Na	Al		
8.55	1.09	0.96	53.84	---	---	---	---	---		

OM = organic matter; C = carbon; N = nitrogen; P = phosphorus; K = potassium; Ca = calcium; Mg = magnesium; S = sulfur; B = boron; Fe = iron; Mn = manganese; Zn = zinc; Na = sodium.

Table 6. Chemical characterization of soils used in this research; samples collected at a depth of 0–0.20 m.

Fertility soil	pH CaCl	pH H ₂ O	P	S	K	Ca	Mg	Al	H+Al	OM
			-----mg.dm ⁻³ ----			-----cmolc.dm ⁻³ -----				-----g.Kg ⁻¹ -----
High *	6.2	5.4	26	25.3	0.22	3.1	0.96	0	2.4	25.33
Average **	6.3	5.5	27	34.3	0.16	2.7	0.93	0	2.1	20.23
Low ***	6.5	4.8	2.3	15.0	0.11	1.1	0.4	0.36	2.6	16.20
	Cu	Fe	Mn	Zn	SB	T	t	V	m	
	-----mg.dm ⁻³ -----					-----cmolc.dm ⁻³ -----		-----%		
High	1.33	52.3	4.0	1.60	4.28	6.68	4.28	4.28	0	
Average	0.23	52.3	2.6	0.90	3.79	5.89	3.79	3.79	0	
Low	0.33	39.3	1.8	0.50	1.61	4.21	1.97	1.97	17.3	

* High fertility = area previously cultivated with soybean, post-harvest planting of *Brachiaria*, application of limestone in 2024 surface. ** Average fertility = area previously cultivated with soybean, post-harvest, without management and application of limestone in 2024 and turning. *** Low fertility = uncultivated area without limestone application in 2024.

Table 7. Textual characterization of soils used in this research.

Fertility Soil	Sand	Silt	Clay	Texture Class
		-----g.kg ⁻¹ -----		
Low	52	279	669	Very clayey
Average	69	262	669	Very clayey
High	148	200	652	Very clayey

Samples collected at a depth of 0–0.20 m.

4.4. Plant Material and Treatments

Maize (*Zea mays* L.) hybrid used was 3858 PWU Pionner®, with superearly cycle of 147 days, plant population per hectare of the order of 60,000 to 55,000, flowering 50 to 72 days after germination, plant height of 1.95 to 2.35 m and ear insertion height of 1.00 to 1.30 m in relation to the ground, with high tolerance to stunting and viruses ground [89]. The seeds were treated with insecticide Cropstar™ at 1 L 100 kg⁻¹ of seeds (Bayer, São Paulo, Brazil) and three insecticide applications of Connect™ under 600 mL ha⁻¹ (Bayer, São Paulo, Brazil) when it comes to plants in the field. Treatments using organic waste were applied in planting and topdressing in different soil fertilities (low, average and high). Organic waste—planting was applied during planting, while organic waste—topdressing was supplied at the V3 stage, both at a rate of 5 tons ha⁻¹. To test benefits linked to organic waste, mineral fertilization was reduced by 15% using a dose of 120 kg ha⁻¹ of NK formulation (suNKiss™, 17% nitrogen and 28% potassium) and urea (45% nitrogen). Phosphorus fertilization was implemented using 150 kg ha⁻¹ of P₂O₅ (32% of phosphorus). Treatment with mineral fertilizer provides a nutritional supply that meets 100% of the crop's necessary nutrient requirements. When it comes to no-fertilizer treatment, do not use fertilizers (mineral or organic). Monitoring was conducted to control pests, including leafhoppers and caterpillars, as well as weeds. At 45 days after planting, physiological evaluations were performed on the plants (phenological stage V10), and soil samples were collected for soil microbiological and chemical analysis.

4.5. Soil Collection and Analysis

To characterize soil attributes, samples were collected from the experimental plots. The samples were subjected to the extraction and subsequent determination process [90]. In the soil samples, pH (CaCl₂), organic matter (g.dm⁻³), P, K, S, Zn, Mn, Cu, Fe and B (mg dm⁻³), Ca, Mg, Al, H+Al (cmolc dm⁻³) were determined, and CEC (cmolc dm⁻³) and V and m (%) were also calculated.

4.6. Measurement of Gas Exchange

Gas exchange was evaluated in all plants and measured in the expanded leaves in the middle region of the plant using an infrared gas analyzer (model LCPro⁺; ADC BioScientific, Hoddesdo, UK) in a chamber under constant CO₂ (twelve-g CO₂ cylinder), photosynthetically active radiation, air-flow rate and temperature conditions at 450 µmol mol⁻¹ CO₂, 800 µmol photons m⁻² s⁻¹, 300 µmol s⁻¹ and 28 °C, respectively, between 10:00 and 12:00 h. The water-use efficiency (WUE) was estimated [91], and the instantaneous carboxylation efficiency (P_N/C_i) was calculated [92].

4.7. Enzymatic Assays and Superoxide Anion

Extraction was performed using 500 mg plant material homogenized with 5 mL of extraction buffer [50 mM phosphate buffer (pH 7.6), 1.0 mM ascorbate and 1.0 mM EDTA] and subsequently centrifuged at 14,000× g for 4 min at 3 °C. Finally, the supernatant was collected [93]. All determinations used a spectrophotometer (model UV-M51, Bel Photonics, Monza, Italy); superoxide dismutase (SOD) activity was measured with 0.2 mL supernatant and 2.8 mL reaction mixture [50 mM phosphate buffer (pH 7.6), 0.1 mM EDTA, 13 mM methionine (pH 7.6), 75 µM NBT and 4 µM riboflavin], expressed in units of mg⁻¹ protein and measured at 560 nm [94]. Catalase (CAT) activity was evaluated using 0.2 mL of supernatant and 1.8 mL of reaction mixture [50 mM phosphate buffer (pH 7.0) and 12.5 mM hydrogen peroxide], presented in µmol H₂O₂ mg⁻¹ protein min⁻¹ and measured at 240 nm [95]. Ascorbate peroxidase (APX) activity was determined with 0.2 mL of supernatant and 1.8 mL of reaction mixture [50 mM phosphate buffer (pH 7.0),

0.5 mM ascorbate, 0.1 mM EDTA and 1.0 mM hydrogen peroxide], expressed in $\mu\text{mol AsA mg}^{-1} \text{ protein min}^{-1}$ and determined at 290 nm [96]. Peroxidase (POX) activity was measured using 0.2 mL of supernatant and 1.78 mL of a reaction mixture [50 mM phosphate buffer (pH 7.0) and 0.05% guaiacol and 20 μL of 10 mM hydrogen peroxide] presented in $\mu\text{mol tetraguaiacol mg}^{-1} \text{ protein min}^{-1}$ and measured at 470 nm [97]. Superoxide anion (O_2^-) was determined using 1 mL of supernatant extracted above and incubated with a reaction mixture [30 mM phosphate buffer (pH 7.60), 0.51 mM hydroxylamine hydrochloride, 17 mM sulfanilamide, 7 mM α -naphthylamine and ethyl ether] determined at 530 nm [98]. Total soluble proteins were analyzed [99].

4.8. Stress Indicators, Chloroplastic Pigments and Growth

Stress indicators were extracted using 500 mg of fresh material and 5 mL of 5% (*w/v*) trichloroacetic acid and subsequently centrifuged at $15,000 \times g$ for 15 min at 3 °C to collect the supernatant [100]. Hydrogen peroxide (H_2O_2) was measured with 0.2 mL of supernatant and 1.8 mL of reaction mixture [2.5 mM potassium phosphate buffer (pH 7.0) and 500 mM potassium iodide] [101]. Malondialdehyde (MDA) was determined using 0.5 mL of supernatant and 1 mL of the reaction mixture (0.5% (*w/v*) thiobarbituric acid in 20% trichloroacetic acid) [102]. Electrolyte leakage (EL) was performed according to the protocol [103]. Photosynthetic pigments chlorophyll *a* (Chl *a*), chlorophyll *b* (Chl *b*), carotenoid (Car) and total chlorophyll (total Chl) were extracted with 40 mg of leaf tissue homogenized in 8 mL of 90% methanol, being determined at 470, 652.4 and 665.2 nm and using a spectrophotometer (model UV-M51, Bel Photonics, Monza, Italy) [104]. The shoot dry matter (SDM) was measured based on constant dry weights (g) after drying in a forced-air ventilation oven at 65 °C, while plant height (PH) and first spike height (FSH) were measured with tape measure, and root collar diameter (RCD) using digital caliper.

4.9. Data Analysis

The normality of residues was verified with the Shapiro–Wilk test. Data were subjected to two-way ANOVA, and significant differences between the means were determined using the Tukey test at a probability level of 5% [105]. Standard deviations were calculated for each treatment. Statistical data analysis was performed using RTM software version 4.4.1 [106].

5. Conclusions

The results obtained in this research confirm the positive influence of organic waste in soils with different fertility levels in corn crops. Benefits described in the biochemical and physiological variables of the plants are observed. Synergistically, the organic waste promoted significant increases in all antioxidant enzymes (superoxide dismutase, catalase, ascorbate peroxidase, and peroxidase), reducing oxidative compounds (malondialdehyde and electrolyte leakage), clearly stimulating the redox mechanism and, consequently, benefiting the photosynthetic machinery, as confirmed by the increases in photosynthesis and chlorophyll contents obtained in this research. These results reveal the comprehensive effect of the organic waste on the soil described in the increases in soil microbiological properties, including the increase in enzymatic activity, organic matter content and nutrient availability to the corn crop, confirmed by the higher biomass yield. The results found in this research are promising, but large-scale application will require future studies aimed at optimizing particle size and maximizing nutrient contents.

Author Contributions: E.M.S.G.L. was the advisor of this project, planning all phases of this research. M.A.F.G. and A.K.d.S.L. conducted the experiment in the field conditions and performed physiologi-

cal, biochemical, nutritional and morphological determinations. L.C. and H.V.d.L. critically revised the manuscript. All authors have read and agreed to the published version of the manuscript.

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