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Gypsum boards and eggshells facilitate the accumulation of dry matter and nutrients in tomato vegetative structures

Placas-de-gesso e casca-de-ovo facilitam o acúmulo de matéria seca e nutrientes em estruturas vegetativas do tomateiro

Placas de yeso y cáscaras de huevo facilitan la acumulación de materia seca y nutrientes en las estructuras vegetativas del tomate

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Abstract
Gypsum boards, eggshells, and urban pruning residues, when accumulated on sidewalks, vacant lots, or within native forests, can pose risks to public, environmental, and financial health. This study aimed to assess whether gypsum boards and eggshells could enhance the accumulation of dry matter and nutrients in tomato plants supplemented with Brazilwood leaves as the sole source of nitrogen. The experimental treatments comprised different doses of gypsum boards powder (0, 100, 200, 400, 800, 1600, and 3200 kg ha^{-1}) alongside a single dose of eggshells at 3200 kg ha^{-1}. Following the transplantation of the Caline IPA tomato cultivar into 5-liter pots, the experiment was conducted in a randomized block design with four replications. Growth indicators and macronutrient content were evaluated at 52 days post-emergence. The lower doses of gypsum boards powder, specifically 100, 200, and 400 kg ha^{-1}, demonstrated over a twofold increase in dry biomass and macronutrient content compared to the control treatment. The doses of 800, 1600, and 3200 kg ha^{-1} resulted in more than an eightfold increase, with the 800 kg ha^{-1} dose being particularly notable for promoting an increase of over thirteen times in these variables. Eggshells increased the number of leaves by 40% and more than doubled both dry biomass and nutrient content. This study suggests that gypsum boards powder, eggshells, and Brazilwood leaves can enhance tomato yield in low-nutrient input systems.
Keywords: *Solanum lycopersicum*; *Paubrasilia echinata*; Urban pruning residues; Semiarid; Calcium; Sulfur.

Resumo
Placas-de-gesso, casca-de-ovo e restolhos de poda urbanos, quando aglutinados em calçadas, em terrenos baldios e/ou na mata-nativa, podem oferecer risco à saúde pública, ambiental e financeira de uma sociedade. Este trabalho objetivou avaliar se placas-de-gesso e a casca-de-ovo podem facilitar o acúmulo de matéria seca e nutrientes em

plantas de tomate suplementadas com folhas de Pau-Brasil como única fonte de nitrogênio. Os tratamentos consistiram de diferentes doses de pó de placas-de-gesso (0; 100; 200; 400; 800; 1600 e 3200 kg ha^{-1}) e de uma única dose de casca-de-ovo: 3200 kg ha^{-1}. Após o transplantio da cultivar de tomate Caline IPA para vasos de 5 L, o experimento foi conduzido em delineamento de blocos ao acaso, com 4 repetições. Aos 52 dias após a emergência, indicadores de crescimento e conteúdo de macronutrientes foram avaliados. As doses mais baixas de pó de placas-de-gesso, 100; 200 e 400 kg ha^{-1}, quando comparadas ao tratamento controle, revelaram incrementos de mais de 2 vezes na biomassa-seca e no conteúdo de macronutrientes; e as doses 800; 1600 e 3200 kg ha^{-1}, incrementos de mais de 8 vezes, destacando-se a dose 800 kg ha^{-1} por ter promovido um incremento de mais de 13 vezes nestas variáveis. A casca-de-ovo incrementou o número de folhas em 40%, e a biomassa-seca e o conteúdo de nutrientes em mais de 2 vezes. Este estudo sugere, portanto, que o pó de placas-de-gesso, da casca-de-ovo e as folhas de Pau-Brasil podem melhorar o rendimento do tomate em sistemas de baixo aporte de nutrientes.
Palavras-chave: *Solanum lycopersicum*; *Paubrasilia echinata*; Resíduos de poda urbanos; Semiárido; Cálcio; Enxofre.

Resumen
Placas de yeso, cáscara de huevo y restos de poda urbanos, cuando se aglutinan en aceras, en terrenos baldíos o en el bosque nativo, pueden ofrecer riesgo a la salud pública, ambiental y financiera de una sociedad. Este estudio tuvo como objetivo evaluar si las placas de yeso y la cáscara de huevo pueden facilitar la acumulación de materia seca y nutrientes en plantas de tomate suplementadas con hojas de Palo Brasil como única fuente de nitrógeno. Los tratamientos consistieron en diferentes dosis de polvo de placas de yeso (0; 100; 200; 400; 800; 1600 y 3200 kg ha^{-1}) y una única dosis de cáscara de huevo: 3200 kg ha^{-1}. Después del trasplante de la variedad de tomate Caline IPA a macetas de 5 L, el experimento se condujo en un diseño de bloques al azar, con 4 repeticiones. A los 52 días después de la emergencia, se evaluaron indicadores de crecimiento y contenido de macronutrientes. Las dosis más bajas de polvo de placas de yeso, 100; 200 y 400 kg ha^{-1}, cuando se compararon con el tratamiento control, revelaron incrementos de más de 2 veces en la biomasa seca y en el contenido de macronutrientes; y las dosis 800; 1600 y 3200 kg ha^{-1}, incrementos de más de 8 veces, destacándose la dosis de 800 kg ha^{-1} por haber promovido un incremento de más de 13 veces en estas variables. La cáscara de huevo incrementó el número de hojas en un 40%, y la biomasa seca y el contenido de nutrientes en más de 2 veces. Este estudio sugiere, por lo tanto, que el polvo de placas de yeso, la cáscara de huevo y las hojas de Palo Brasil pueden mejorar el rendimiento del tomate en sistemas de bajo aporte de nutrientes.
Palabras clave: *Solanum lycopersicum*; *Paubrasilia echinata*; Residuos de poda urbanos; Semiárido; Calcio; Azufre.

1. Introduction

Although gypsum boards, eggshells, and urban pruning residues are classified as low-risk solid waste for the environment under Law 12,305 (National Solid Waste Policy), these materials are often removed from public roads and disposed of in landfills due to their large volume and the potential risks they pose to public safety and environmental pollution when accumulated on sidewalks, vacant lots, or in native forests. However, public funds allocated for the removal of this debris rarely return to public coffers. Thus, a simpler solution to this financial loss would be to transform solid waste into inputs for the agricultural system. For example, gypsum boards could be converted into agricultural gypsum, eggshells into calcitic limestone, and urban tree leaves into green manure.

The Araripe Sertão region of Pernambuco consists of ten municipalities: Araripina, Trindade, Ipubi, Bodocó, Exu, Moreilândia, Ouricuri, Santa Cruz, Santa Filomena, and Granito. The urban vegetation cover in this region averages around 77% (IBGE-SIDRA, 2021). Thus, the pruning residues from this urban vegetation, particularly leaves of tree legumes, could be utilized as green manure on some of the 25,000 small family farms in the Araripe Sertão (SDT/MDA, 2015). This practice would enhance productivity, improve cash flow, and reduce production costs for farmers in Pernambuco while simultaneously conserving the soil. Moreover, several municipalities in this region (Araripina, Trindade, Ipubi, Bodocó, and Ouricuri) are part of the Gypsum Pole. The Gypsum Pole, which produces over 1.45 million tons of gypsum ore and accounts for 89% of Brazil's production, generates gypsum waste through ore extraction, precast material production, and construction and demolition activities. In this context, one of the most effective strategies to mitigate the environmental impact in this region would be to foster partnerships between the construction industry and the agricultural sector, which consumes approximately 4.5 million tons of gypsum annually (Barbosa et al., 2014; Santos et al., 2014).

Although eggshells have significant agronomic potential as calcitic limestone, their primary producers frequently utilize or dispose of them inadequately, either by burning them in barbecues or discarding them in landfills. Both practices result in CO_2 emissions, a greenhouse gas that contributes to global warming. Considering that the construction industry accounts for one-third of global greenhouse gas emissions (Salino et al., 2021), there is an urgent socio-environmental and economic need to transform solid waste into agricultural (or other) inputs. This transformation aims to facilitate recycling and reduce the carbon footprint of the industry responsible for generating such waste.

The interaction between the construction industry and the agricultural sector has been pioneeringly tested with *Crotalaria retusa* supplemented with 50 g of gypsum boards powder in a semi-humid tropical climate. Such study observed a 50% increase in both root and total plant dry biomass (Neto et al., 2015). However, no studies have been found in the literature correlating highly calcium-demanding crops (such as tomatoes) with calcium supplementation using gypsum boards powder or eggshells, combined with fertilization from urban pruning residues of Brazilwood (*Paubrasilia echinata*) as the sole nitrogen source in a semi-arid climate. Based on this information, the following hypothesis was formulated: Do tomato plants that receive urban pruning residues of Brazilwood (as the sole nitrogen source) exhibit enhanced growth when supplemented with gypsum boards powder or eggshells? This is the question we aim to address in this article.

To investigate this, we measured under field conditions the dry biomass (65°C, 72h) of the root, stem, leaf, and aerial parts, the root-to-shoot ratio, plant height, number of leaves, stem diameter, root volume, and macronutrient content in the industrial tomato cultivar Caline IPA 6 supplemented with increasing doses of gypsum boards powder (0, 100, 200, 400, 800, 1600, and 3200 kg ha^{-1}). This study, therefore, aims to evaluate whether gypsum boards powder or eggshells facilitate the accumulation of dry matter and nutrients in tomato plants supplemented with Brazilwood leaves as the sole nitrogen source.

2. Methodology

Climatic conditions in the experimental area

The experiment followed the quantitative laboratory research methodology (Pereira et al., 2018). It was established and conducted under field conditions in the municipality of Trindade-PE, Brazil, known locally as the Gypsum Capital. Trindade is situated at 7º 47' 9.2033'' S, 40º 16' 56.645'' W, and at an altitude of 518 meters. The city is part of the Araripe Gypsum Pole, along with Araripina, Bodocó, Ipubi, and Ouricuri. The region's climate is classified as BSwh (Araujo, 2004; Damasceno, 2020; Vergara et al., 2024).

Soil fertilization for the experiment

A Ferralsol (WRB/FAO, 2015)—or Latossolo Vermelho-Amarelo eutrófico (EMBRAPA, 2018)—, with chemical characteristics detailed by Vergara et al. (2024), was collected from the School of Agricultural Sciences of Araripina (FACIAGRA) and sieved in Trindade-PE. Three kilograms of air-dried fine soil were then placed into the experimental units, which were plastic pots with a capacity of 5 liters. Following the fertilization manual of the Pernambuco state (Cavalcanti, 2008), the soil was fertilized with the equivalent of 160 kg ha^{-1} of N (11.0 g per pot of finely ground Brazilwood leaves), 300 kg ha^{-1} of P_2O_5 (2.25 g per pot of single superphosphate), 180 kg ha^{-1} of K_2O (0.28 g per pot of potassium chloride), and 20 kg ha^{-1} of micronutrients (0.03 g per pot of FTE BR 12). Additionally, potassium was applied both at planting and as a top dressing.

Nitrogen fertilization

Brazilwood (*Paubrasilia echinata*) pruning residues, primarily consisting of leaves, were utilized as the sole nitrogen source. These residues were collected from public roads in Araripina-PE, initially dried at 60 ºC for 48 hours in an oven at the

School of Agricultural Sciences of Araripina (FACIAGRA), then ground and sifted through an ABNT No. 20 sieve (0.840 mm). The resulting macronutrient concentrations were (in g kg^{-1}): N = 19.44; P = 0.80; K = 9.70; Ca = 12.60; Mg = 2.18; S = 3.20. Each pot containing 3 kg of soil received 11 g of *P. echinata*.

Collection and preparation of gypsum boards and eggshells

The unusable gypsum boards and eggshells used in this study were collected from Villa dos Algodões in the municipality of Trindade-PE. After collection, the eggshells were dried in an oven at 60 ºC for 48 hours, while the gypsum boards were dried at room temperature. Following drying, these residues were crushed and sifted through an ABNT No. 50 sieve (0.300 mm). The particle size and chemical composition of the crushed eggshells are detailed in Vergara et al. (2024). Each pot containing 3 kg of soil received 4.37 g of crushed eggshells.

Experimental design and treatments

The treatments involved the application of increasing doses of gypsum boards powder (0, 100, 200, 400, 800, 1600, and 3200 kg ha^{-1}—equivalent to 0, 0.045, 0.09, 0.18, 0.37, 0.73, and 1.46 g kg^{-1} of soil) and a single dose of eggshells equivalent to 3200 kg ha^{-1} to tomato plants (industrial cultivar Caline IPA 6), resulting in a total of eight treatments. These treatments were arranged in the field using a randomized block design with four replications. Gypsum boards powder, eggshells, and green manure from Brazilwood leaves were applied all at once during planting and thoroughly mixed with the soil. After thinning, one plant per pot was left. The IPA 6 cultivar, a low-growing variety used in the region as a table tomato, was grown with semi-staking using vertical stakes, a practice adopted by local farmers (Silva et al., 2014). Soil moisture was maintained close to field capacity by irrigating the pots twice a day with running water.

Measurements and statistics

Data collection for the experiment was conducted 52 days after emergence, assessing the following characteristics: dry biomass (65°C, 72h) of the root, stem, leaf, and aerial parts; root-to-shoot ratio; plant height; number of leaves; stem diameter; root volume; and macronutrient content. The data were initially tested for ANOVA requirements using Bartlett's test for homoscedasticity, the Shapiro-Wilk test for normality, and Tukey's test for additivity. Subsequently, analysis of variance (ANOVA) was performed. Comparisons of gypsum boards doses were conducted using regression analysis, while comparisons between gypsum and eggshell treatments were made using Tukey's test ($p<0.05$). Statistical analyses were performed using R-project software version 3.4.1 (Team, 2023). Results are presented as mean ± standard error.

3. Results

The analysis of the dry biomass of the stem, leaf, and aerial parts across treatments—including all doses or just the lower doses of gypsum boards powder (100, 200, and 400 kg ha^{-1}) and eggshell (Figure 1)—reveals that, compared to the control treatment (0 kg ha^{-1}), all treatments with additional calcium improved the growth of tomato plants grown with finely ground Brazilwood urban pruning residues as the sole nitrogen source under the semi-arid conditions of the Pernambuco Gypsum Pole. The doses of gypsum boards powder resulted in increases ranging from 15 to 223% in root dry biomass, 83 to 1300% in stem biomass, and 139 to 2013% in leaf biomass. Eggshells, following the trend of gypsum boards powder, increased the dry biomass of the stem, leaf, and aerial parts by 143%, 230%, and 193%, respectively. Under the conditions of this experiment, two major groups of gypsum doses emerged: (i) those that increased aerial biomass by 2 to 3 times—100, 200, and 400 kg ha^{-1}—compared to the control (0 kg ha^{-1}), and (ii) those that increased aerial biomass by more than 10 times—800, 1600, and 3200 kg ha^{-1}—with the 800 kg ha^{-1} dose being particularly notable, as it was the only one correlated with the

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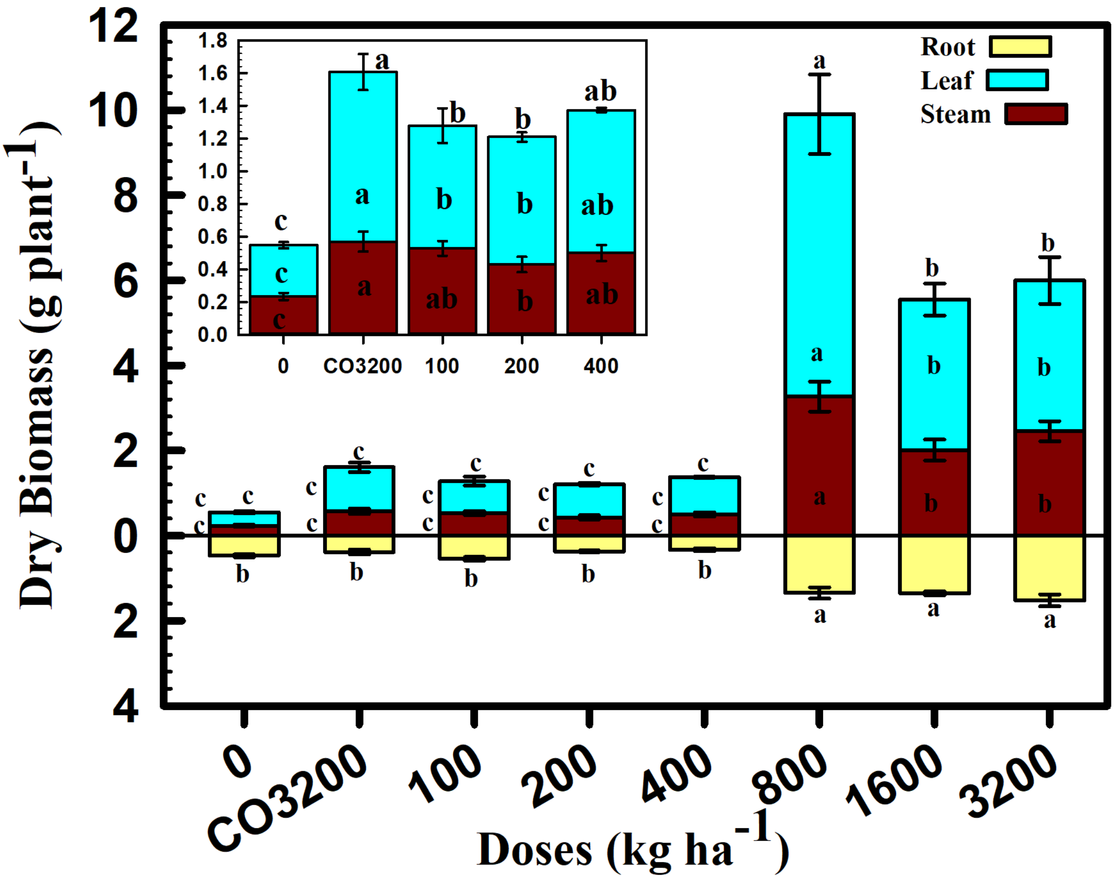
maximum tomato growth, achieving an 18-fold increase over the control (Figure 1). Eggshells (3200 kg ha^{-1}), despite deviating from the higher doses of gypsum boards powder, tripled the dry biomass of the tomato's aerial parts, placing them in the first group. This can be attributed to the lower solubility of calcium carbonate compared to calcium sulfate. Additionally, plants receiving 800 and 1600 kg ha^{-1} of gypsum boards powder exhibited height, number of leaves, root volume, and stem diameter comparable to those of the 3200 kg ha^{-1} gypsum boards powder treatment, but superior to those of the other treatments (Figure 2). Notably, plants treated with 3200 kg ha^{-1} of eggshells distinguished themselves from the control treatment by increasing the number of leaves by 40% (Table 1).

Figure 1 - Dry Biomass of Root, Stem, Leaf, and Aerial Parts (in g $plant^{-1}$) of tomato plants (industrial cultivar Caline IPA 6) fertilized with urban pruning residues of Brazilwood (finely ground) as the sole nitrogen source in the Pernambuco Gypsum Pole. Some plants did not receive gypsum boards powder or eggshells (control treatment, 0 kg ha^{-1}); others received 100, 200, 400, 800, 1600, or 3200 kg ha^{-1} of gypsum boards powder; and the remaining received 3200 kg ha^{-1} of eggshells (CO3200). Among the doses, values followed by the same lowercase letters do not differ significantly, as determined by Tukey's test ($p < 0.05$). Error bars represent the standard error of the mean ($n = 4$).



Source: Authors.

This figure clearly demonstrates that all doses of gypsum boards powder (and eggshells) enhanced the growth of tomato plants cultivated under semi-arid conditions and fertilized with urban pruning residues of Brazilwood as the sole nitrogen source.

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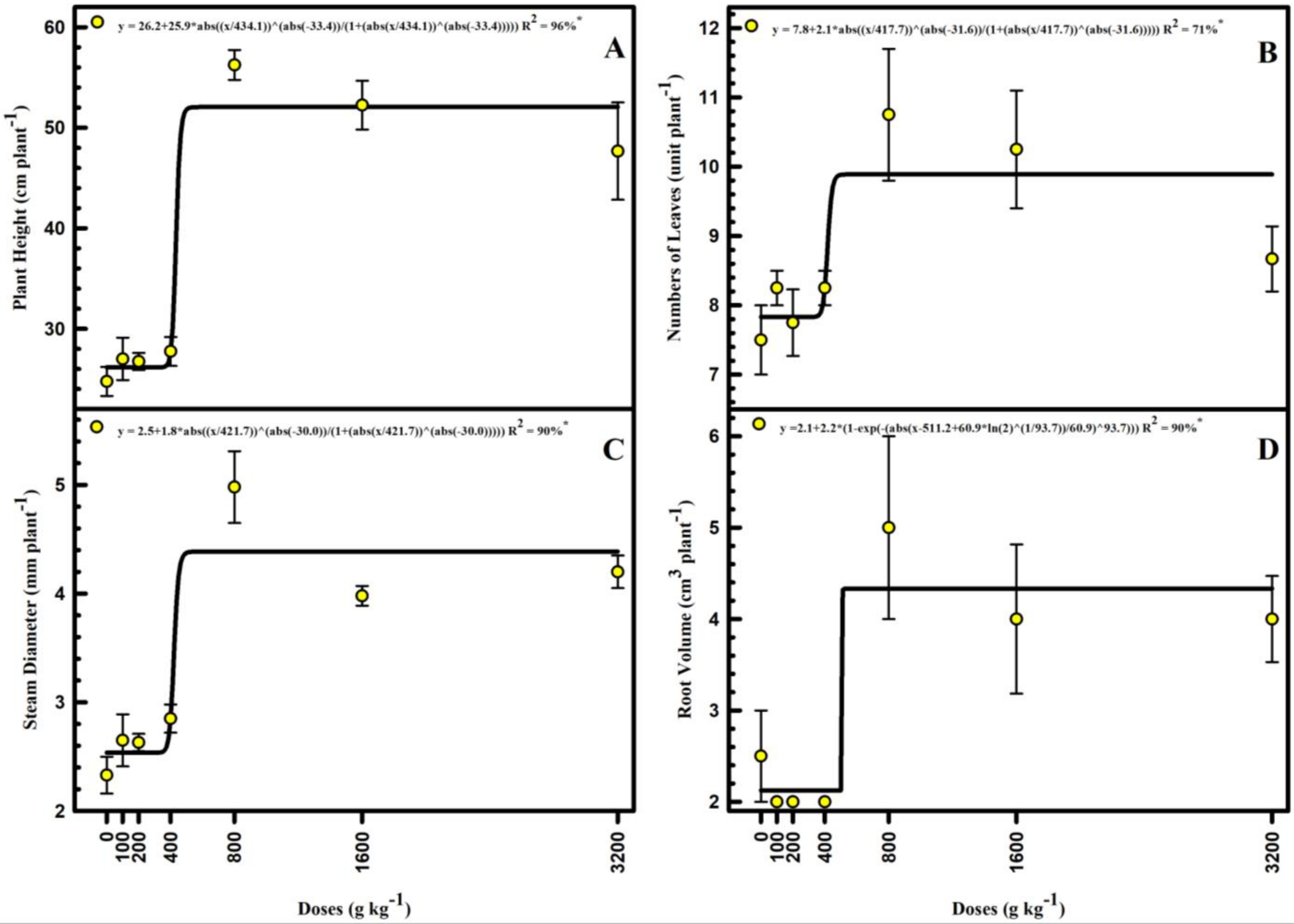
Figure 2 - Plant Height (**A**), Number of Leaves (**B**), Stem Diameter (**C**), and Root Volume (**D**) of tomato plants (industrial cultivar Caline IPA 6) fertilized with urban pruning residues of Brazilwood (finely ground) as the sole nitrogen source in the Pernambuco Gypsum Pole. Some plants did not receive gypsum boards powder (control treatment, 0 kg ha⁻¹); others received 100, 200, 400, 800, 1600, or 3200 kg ha⁻¹ of gypsum boards powder. Error bars represent the standard error of the mean (n = 4). * Significant according to F-test ($p < 0.05$).



Source: Authors.

Tomato plants that received 800, 1600, and 3200 kg ha⁻¹ of gypsum boards powder exhibited greater plant height, stem diameter, number of leaves, and root volume compared to the other treatments.

Table 1 - Plant Height, Stem Diameter, Number of Leaves, and Root Volume of tomato plants (industrial cultivar Caline IPA 6) fertilized with urban pruning residues of Brazilwood (finely ground) as the sole nitrogen source in the Pernambuco Gypsum Pole. Some plants did not receive gypsum boards powder or eggshells (control treatment, 0 kg ha^{-1}); others received 100, 200, or 400 kg ha^{-1} of gypsum boards powder; and the remaining received only 3200 kg ha^{-1} of eggshells (CO3200).

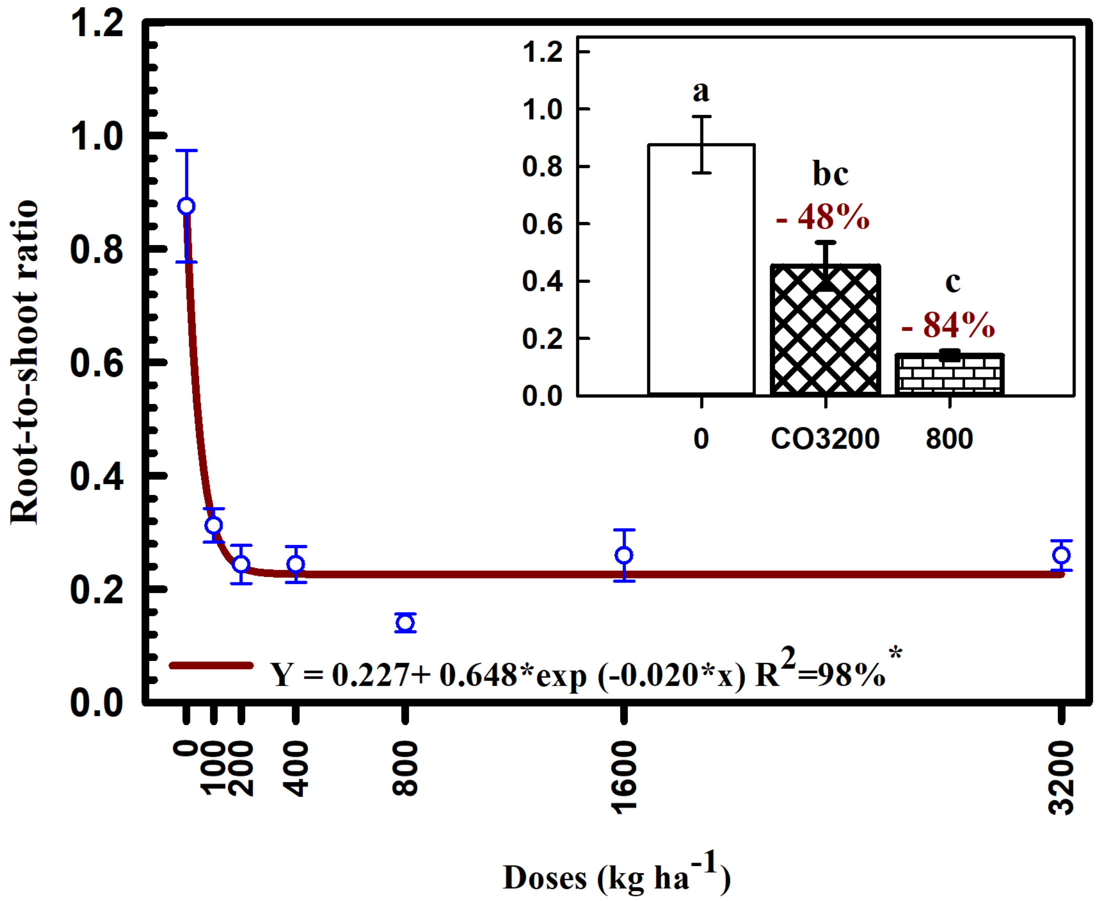
Treatments (kg ha^{-1})	**Plant Height (cm $plant^{-1}$)**	**Steam Diameter (mm $stem^{-1}$)**	**Number of Leaves (unit $plant^{-1}$)**	**Root Volume (cm^3 $plant^{-1}$)**
0	24.75 ± 1.44	2.33 ± 0.17	7.50 ± 0.50 b	2.00 ± 0.00
100	27.00 ± 2.12	2.65 ± 0.24	8.25 ± 0.25 ab	2.00 ± 0.00
200	26.75 ± 0.85	2.63 ± 0.08	7.75 ± 0.48 b	2.00 ± 0.00
400	27.75 ± 1.44	2.85 ± 0.13	8.25 ± 0.25 ab	2.00 ± 0.00
CO3200	31.25 ± 1.65	2.90 ± 0.10	10.50 ± 0.65 a	2.00 ± 0.00
CV (%)	11.31	11.58	10.76	0.0%

Means ± SE (n = 4) followed by the same lowercase letters within a column are not significantly different (Tukey test, $p < 0.05$). SE: standard error. CV%: coefficient of variation. Source: Authors.

Plants that received eggshells had a higher number of leaves compared to those in the control treatment.

The root-to-shoot ratio exhibited an exponential decay under the conditions of this experiment (Figure 3). Treatments with gypsum boards powder reduced this growth indicator by more than two times compared to the control, with the 800 kg ha^{-1} dose particularly notable for reducing the root-to-shoot ratio by more than six times. This reduction did not adversely affect water and nutrient absorption, as the gypsum treatments explored a soil volume equal to or greater than that of the control plants. Additionally, eggshells, compared to the control treatment, resulted in a 48% reduction in the root-to-shoot ratio. However, the 800 kg ha^{-1} dose of gypsum boards powder went further, reducing this growth indicator by 84%.

Figure 3 - Ratio of root-to-shoot biomass of tomato plants (industrial cultivar Caline IPA 6) fertilized with urban pruning residues of Brazilwood (finely ground) as the sole nitrogen source in the Pernambuco Gypsum Pole. Some plants did not receive gypsum boards powder or eggshells (control treatment, 0 kg ha⁻¹); others received 100, 200, 400, 800, 1600, or 3200 kg ha⁻¹ of gypsum boards powder; and the remaining received only 3200 kg ha⁻¹ of eggshells (CO3200). Values followed by the same lowercase letters among doses are not significantly different, as determined by Tukey's test ($p < 0.05$). * Significant according to F-test ($p < 0.05$). Error bars represent the standard error of the mean (n = 4).

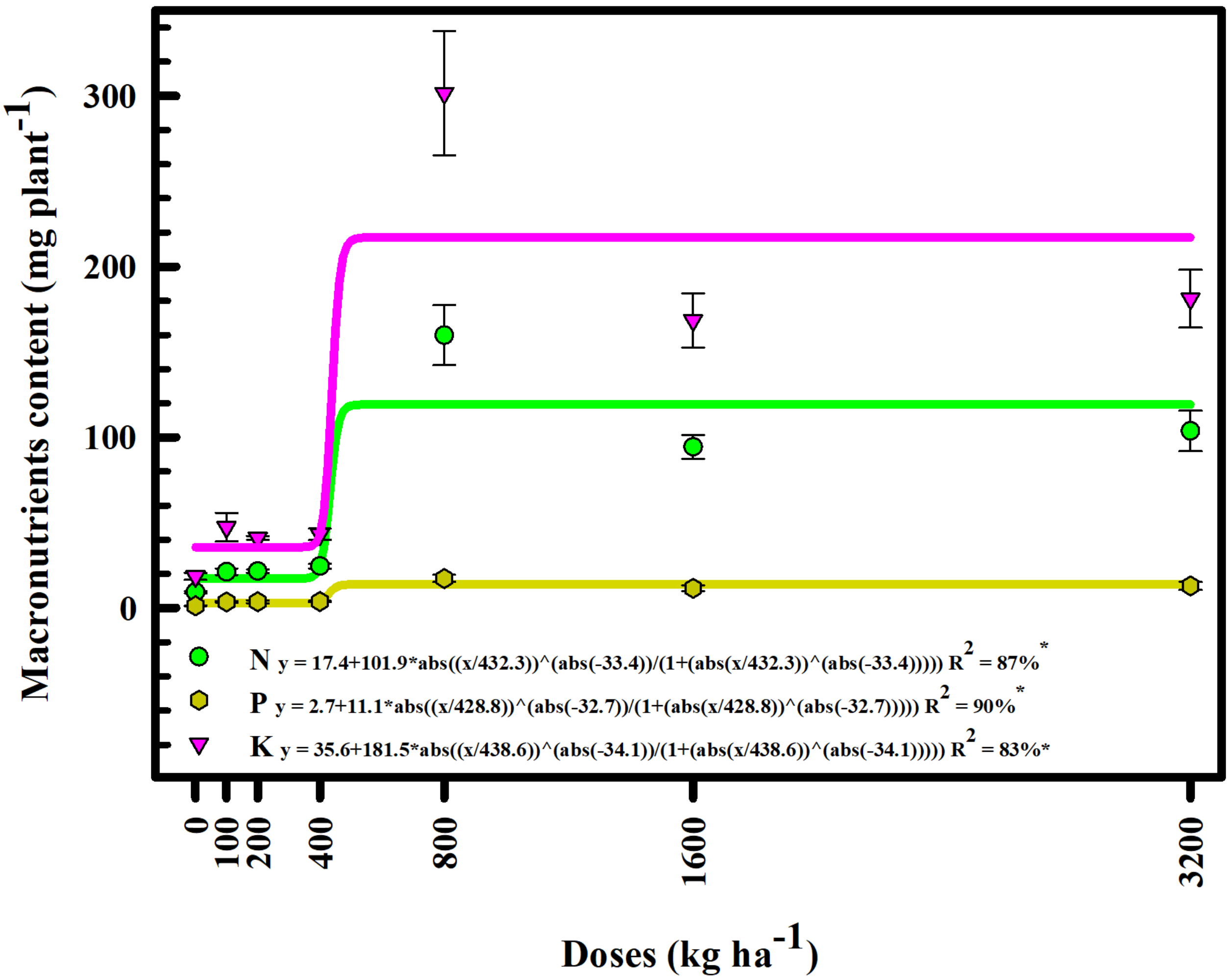


Source: Authors.

This figure shows that, in general, treatments with gypsum boards powder or eggshells reduced the root-to-shoot ratio of tomato plants by more than two times compared to plants that did not receive either gypsum powder or eggshells.

The macronutrient content followed the same pattern as the tomato plant biomass, revealing two main groups of gypsum boards powder doses: those that increased N, P, and K by 2 to 3 times (100, 200, and 400 kg ha⁻¹ of gypsum boards powder), and those that increased these elements in the plant biomass by more than 8 times (800, 1600, and 3200 kg ha⁻¹). Among the doses studied, the 800 kg ha⁻¹ dose stood out for accumulating 17, 13, and 16 times more N, P, and K, respectively, compared to the control treatment (Figure 4). Similarly, eggshells increased N content by 4 times, and P and K contents by 3 times compared to the control treatment, bringing eggshells close to the lower doses of gypsum boards powder (100, 200, and 400 kg ha⁻¹) in terms of nutrient accumulation (Table 2).

Figure 4 - Nitrogen (N), phosphorus (P), and potassium (K) content in tomato plants (Caline IPA 6 cultivar) fertilized with urban pruning residues from Brazilwood (finely ground) as the sole nitrogen source in the Pernambuco Gypsum Pole region. Some plants did not receive gypsum boards powder (control treatment, 0 kg ha^{-1}); others received 100, 200, 400, 800, 1600, or 3200 kg ha^{-1} of gypsum powder. Error bars represent the standard error of the mean (n = 4). * Significant according to the F test ($p < 0.05$).



Source: Authors.

In the figure above, two major groups of gypsum boards powder doses can be distinguished: one group, with nutrient accumulation more than 2 times greater than the control treatment, and another group, with nutrient content 8 times higher than the control.

Table 2 - Nutrient content in tomato plants (industrial cultivar Caline IPA 6) fertilized with urban pruning residues from Brazilwood (finely ground) as the sole nitrogen source in the Pernambuco Gypsum Pole. Some plants did not receive gypsum boards powder or eggshells (control treatment, 0 kg ha⁻¹); others received 100, 200, or 400 kg ha⁻¹ of gypsum boards powder; and the remaining plants received only 3200 kg ha⁻¹ of eggshells (CO3200).

Treatments (kg ha^{-1})	**N**	**P**	**K**
		mg plant^{-1}	
0	9.3±0.6 b	1.3±0.2 b	18.5±2.0 b
100	21.1±1.9 ab	3.6±0.5 ab	47.3±8.3 a
200	21.6±1.0 ab	3.7±0.8 ab	41.0±1.1 a
400	24.5±1.4 a	3.9±0.4 ab	43.2±3.3 a
CO3200	33.1±5.2 a	4.0±0.7 a	55.7±6.0 a
CV (%)	23.81	33.9	23.91

Means ± SE (n=4) followed by the same lowercase letters in a column do not differ significantly (Tukey's test, $p<0.05$). SE: standard error. CV%: coefficient of variation. Source: Authors.

In Table 2, it can be observed that the nutrient content in tomato plants fertilized with eggshells is comparable to that of plants treated with gypsum doses of 100, 200, and 400 kg ha⁻¹, but significantly higher than that of plants in the control treatment.

4. Discussion

EMBRAPA demonstrates that agricultural gypsum doses between 200 and 6000 kg ha⁻¹ are sufficient to promote plant growth in both annual and perennial crops. For instance, increases of 282 and 260% were observed in the dry matter of *Brachiaria brizantha* and *B. decumbens* cultivated with gypsum applications of 3000 and 200 kg ha⁻¹, respectively (de Sousa et al., 2001). This theoretical framework supported our study on the effect of gypsum boards powder on tomato plants, with doses ranging from 100 to 3200 kg ha⁻¹. We opted for gypsum boards powder rather than gypsum fragments because the granulation of the fertilizer influences its reactivity in the soil (Novais et al., 2007). These and other methods have shown that gypsum from the construction industry can significantly affect the growth of tomato plants, which are calcium-demanding, when fertilized with green manure from Brazilwood leaves as the sole nitrogen source.

All calcium treatments altered the phenotypic plasticity of the tomato plants. Among the variables assessed, the root-to-shoot ratio provides evidence for this alteration, as it was lower in the calcium treatments compared to the control (0 kg ha⁻¹). In other words, plants that received an additional supply of calcium, whether through gypsum boards powder or eggshells, invested more in shoot growth than in root growth, while the control treatment favored root growth over shoot growth. These data indicate that incorporating gypsum boards powder (or even eggshells) into the soil improves root distribution within the soil profile. This improvement is further evidenced by the greater root system volume observed in treatments with 800, 1600, and 3200 kg ha⁻¹ of gypsum boards powder.

A well-distributed root system within the soil profile (or even in a pot) facilitates the interception of water and nutrients, reducing the chances of losses such as leaching or ammonia volatilization to other open systems outside the soil. Water entering plant tissue not only carries essential nutrients but also improves the plant's water status. This allows the tomato plant, for example, to reduce abscisic acid concentration to a level where it may open its stomata even during warmer parts of the day. The increased transpiration resulting from this process enhances the uptake of water and nutrients and improves photosynthetic activity (Ker et al., 2015; Lepsch, 2021; Taiz et al., 2016).

In this study, we observed evidence suggesting that treatments with additional calcium supply enhanced both photosynthetic capacity and nutrient and water absorption. Specifically: (i) the number and dry mass of leaves were consistently higher in the calcium treatments compared to the control (Figures 1 and 2; Table 1); (ii) the diameter and dry matter accumulation in the steam were also consistently greater in the calcium treatments than in the control (Figures 1 and 2); and (iii) the nutrient content followed the same trend as the aforementioned variables (Figure 4, Table 2). Previous studies have shown similar results (de Sousa et al., 2008; de Sousa et al., 2001; Novais et al., 2007), but with agricultural gypsum rather than construction plaster. For instance, Leucaena grown under a gypsum application of 6000 kg ha^{-1} exhibited a 55% increase in dry matter yield, and nutrient absorption (N, P, K, Ca, Mg, and S) increased by 41 to 64% (de Sousa et al., 2001).

In our study, the increases in dry matter of the aerial parts ranged from 120 to 1707%, and in nutrients, from 121 to 1621%. This suggests that gypsum application not only promotes greater accumulation of water and nutrients in the plant's vegetative structures (stem and leaves) but also enhances the storage of non-structural carbohydrates, which are later remobilized for fruit production with greater fresh weight. Indeed, soybeans and tomatoes with higher numbers and dry mass of branches, respectively, produced more fruits (Liang et al., 2022; Vergara et al., 2024). But how does hemihydrated gypsum ($CaSO_4$.1/2 H_2O) from construction plaster affect the plant, particularly the tomato plant?

One can attempt to address the question above using two main narratives that complement each other. The first involves the supply of calcium, and the second includes the supply of sulfur to the plant, both of which are nutrients released by gypsum boards powder and Brazilwood leaf green manure.

Regarding calcium supply, there would be an increase in the concentration of this nutrient in the vacuole due to the improved distribution of roots in the soil mentioned earlier. This increase would be electrically balanced in the vacuole by organic anions, such as malate and citrate, derived from the decomposition of Brazilwood green manure, and/or by inorganic anions, such as sulfate (derived from gypsum boards and the mineralization of Brazilwood leaf green manure) and chloride (from irrigation water). The accumulation of calcium in the vacuole would make the osmotic potential of the vacuole even more negative, progressively lowering the plant's water potential below that of the rhizosphere. This would act as a conduit for water in the soil, channeling water from the soil toward the tomato plant (Lepsch, 2021; Sposito, 2008; Taiz et al., 2016).

From the second perspective, the role of calcium is complemented by the role of sulfur and its derivatives. Sulfur is involved in functional groups (such as -SH), coenzymes (such as urease), amino acids (such as cysteine), tripeptides (such as glutathione), and proteins (such as thioredoxin). It also extends to secondary metabolites (such as allicin and glucosinolates) and lipids (such as sulfolipids) in biological membranes.

In cysteines, sulfur acts in the form of -SH functional groups. These functional groups enable cysteine residues within a polypeptide chain to form both reversible and permanent disulfide bonds. Reversible disulfide bonds are crucial for protein aggregation and denaturation during cellular dehydration events. Just as calcium from gypsum boards improves the water status of the tomato plant, -SH groups tend to form more permanent disulfide bonds rather than reversible ones, even under abiotic stress conditions such as heat, drought, or frost damage, leading to greater resistance to dehydration. Thus, calcium nutritionally acts as an inactivator of reversible disulfide bonds in polypeptide chains, highlighting a gap regarding the synergistic effects of these two nutrients on the tomato plant (Levitt, 1980; Tomati & Galli, 1979). Therefore, research aimed at improving tomatoes by focusing on reducing the reactivity of -SH groups in polypeptides with high cysteine content could be pertinent to avoid protein aggregation and denaturation in stressful environments.

Glutathione, a tripeptide with a powerful antioxidant function in chloroplasts, stores about 90% of the organic sulfur in the thiol-soluble fraction of the plant. The remaining 10% is distributed among other sulfur compounds, with thioredoxin standing out as an important oxidoreductase protein in the photosynthetic process (Cakmak & Marschner, 1992; Dekok, 1993; Schurmann, 1993).

The concentration of glutathione in the leaves is significantly higher than in the roots. In the chloroplasts, leaves concentrate about 50% of this tripeptide to act as a defensive barrier against reactive oxygen species, such as hydrogen peroxide and oxygen radicals. Although the concentration of glutathione in the roots is lower than in the leaves, it is still four times higher than that of cysteine, highlighting its crucial role in detoxifying reactive oxygen species. In contrast to glutathione, thioredoxin functions as a carrier of reduced compounds (from photosystem I for CO_2 assimilation) or as a carrier of oxidized compounds toward photosystem I, establishing an intermolecular redox activity. In chloroplasts, after being reduced by ferredoxin, this protein activates Calvin cycle enzymes. In the cytoplasm, on the other hand, it is reduced by NADPH and activates enzymes such as fructose 1,6-bisphosphatase (Marschner, 2011; Nieto-Sotelo & Ho, 1986; Rennenberg & Lamoureux, 1990).

In light of these functions of glutathione and thioredoxin, it is easier to understand why plants subjected to gypsum application showed increases ranging from 13 to 114% in stem diameter and from 3 to 40% in leaf number compared to the control without gypsum application. The gypsum boards powder appears to protect the tomato plant against abiotic stress while simultaneously promoting photosynthesis. Therefore, our data suggest that gypsum powder is effective in protecting the plant from oxidative stress, thereby maximizing its genetic potential and enhancing the photosynthetic process.

Sulfur sufficiency in plants, achieved through the application of fertilizers with high sulfur content, leads to increased resistance to both abiotic (as previously mentioned) and biotic stress (Rausch & Wachter, 2005). Regarding biotic resistance, two secondary metabolites are particularly noteworthy—even though there are no reports of their occurrence in tomatoes. The first compound is alliin, which accumulates 80% of sulfur in onions (*Allium cepa*). When cellular rupture occurs in onions for any reason, alliin is hydrolyzed by alliinases to form allicins, which subsequently act as precursors to secondary metabolites, including mono- and disulfides with characteristic odors. Another significant group of secondary metabolites are glucosinolates, which accumulate in the vacuole of some plants. When mechanical damage or sulfur demand occurs, they are broken down into glucose, sulfate, and volatile compounds (such as isothiocyanates in *Brassica napus*) by the enzyme myrosinase. Sulfate and volatile compounds then enter the reassimilation pathway to supply sulfur to the plant. Additionally, sulfate can form sulfate esters, non-reduced sulfur that forms sulfolipids in biological membranes, representing 5% of chloroplast lipids, specifically in thylakoid membranes. Sulfolipids are responsible for regulating iron transport across biomembranes and are also correlated with plant salt tolerance (Erdei et al., 1980; Höglund et al., 1991; Jones & Takemoto, 2004; McCully et al., 2008; Schnug, 1993; Stuiver et al., 1978; Wink, 1993). Therefore, it is essential to investigate the sulfur-rich secondary metabolites involved in tomato plant defense against biotic stress when supplemented with gypsum boards powder.

Under the lens of the aforementioned literature, our data suggest that the use of gypsum boards powder in agriculture not only represents an important method for utilizing solid waste but also enhances calcium and sulfur accumulation in plants. This accumulation forms a crucial arsenal for combating both abiotic and biotic stresses, which increasingly act in tandem across the planet. This is particularly relevant in the Brazilian semi-arid region, characterized by intense solar radiation, drought, annual evapotranspiration of up to 2000 mm, high air and soil temperatures, sodicity, salinity, and agricultural pests capable of causing productivity losses of more than 80% (Bento et al., 2002; Rivero et al., 2022; Vergara et al., 2024).

Sulfur entered our experiment through two main pathways: gypsum boards, containing 16% S, and the green manure from Brazilwood leaves, containing 3.20% S. The 16% S from gypsum boards supplemented the approximately 5% inorganic S typically present in the soil, while the 3.20% S from Brazilwood leaves contributed to the more than 95% organic S that replenishes the soil. In the soil, inorganic sulfur is initially converted into sulfate esters, or more specifically, the C-O-S fraction, by microorganisms that utilized, among other residues, Brazilwood leaf green manure as a source of N and C. Subsequently, sulfate esters are converted into amino acids, i.e., the C-S fraction. Both sulfur fractions, C-O-S and C-S, are organic sources of sulfur (Dedourge et al., 2004; Ghani et al., 1993; Paul & Frey, 2023; Vong et al., 2003).

By fertilizing the soil with Brazilwood leaf green manure, we aimed to predominantly supply the soil biota with nitrogen and the C-S sulfur fraction. The C-S fraction represents about 90% of the total sulfur in the plant, primarily derived from chloroplasts, specifically from thylakoid membrane sulfolipids. This fraction comprises S-peptides and S-sulfonates, which are oxidized to sulfate in the soil by sulfatases typically produced by actinobacteria and pseudomonas. S-sulfonates can also be converted to SO_3^{2-} (sulfite) through a process known as desulfurization, conducted by flavin-dependent monooxygenases present in some bacterial genera, such as *Variovorax*, *Polaromonas*, and *Rhodococcus.* Subsequently, SO_3^{2-} can be incorporated into microbial biomass (Benning, 1998; Schmalenberger et al., 2008; Schmalenberger et al., 2009; Schmalenberger et al., 2010).

The sulfur released by gypsum boards and Brazilwood leaf green manure was utilized not only by the plants and bacteria but also by saprotrophic fungi (such as *Penicillium*, *Neurospora*, and dark septate endophytic fungi) and mycorrhizal fungi. In these fungi, sulfate is initially reduced to sulfide and then converted into cysteine. The remaining sulfur is stored in vacuoles, either as sulfate or as glutathione (Jennings, 1995; Paul & Frey, 2023; Vergara & Araujo, 2024; Vergara, Araujo, Souza, et al., 2019; Vergara, Araujo, Sperandio, et al., 2019; Vergara et al., 2018; Vergara et al., 2017; Vergara et al., 2023; Yang et al., 2010). As mentioned earlier, glutathione helps alleviate abiotic stress in plants.

In microaggregates that accumulate green manure and water, anaerobiosis can occur, favoring the conversion of sulfate to sulfide by organotrophic bacteria such as *Desulfovibrio*, *Desulfobacter, Desulfococcus*, *Desulfotomaculum*, and *Archaeoglobus*. Conversely, sulfide can be oxidized to sulfate and its intermediates by chemolithotrophic bacteria—obligate aerobes (*Thiobacillus* and *Acidithiobacillus*) and anaerobes (*Thiobacillus denitrificans*)—and heterotrophs such as *Bacillus*, *Arthrobacter, Micrococcus*, and *Pseudomonas*. Heterotrophs, which are stimulated by elemental sulfur in soils with high organic carbon, perform only partial oxidation, for example, from thiosulfate to sulfate (Jennings, 1995; Paul & Frey, 2023). It is worth speculating that the oxidation of sulfide by these microorganisms may have contributed to buffering the soil pH, thereby maintaining favorable conditions for tomato cultivation.

The calcium utilized by microorganisms (fungi and bacteria) would first be converted into calcium oxalates. In fungi, calcium oxalates regulate cytosolic pH and control the Ca^{2+} pool necessary for cellular signaling from the external membrane to the cytoplasm. Oxalotrophic bacteria, such as *Ralstonia eutropha* and *Xanthobacter autotrophicus*, would then convert calcium oxalate into calcite via the oxalate-carbonate pathway, using oxalate as an energy source (Jennings, 1995; Martin et al., 2012).

The oxalate-carbonate pathway might thus explain why toxic aluminum is neutralized in soils subjected to gypsum treatment. This neutralization is not directly related to gypsum but to calcite. Furthermore, fertilizations with sources of calcium and sulfur, by feeding the oxalate-carbonate pathway and sulfide oxidation, should be considered as management practices capable of buffering soil pH within the optimal range for crops.

From the above, it is clear that eggshells, gypsum boards, and green manure with Brazilwood leaves have stimulated soil biology and promoted plant growth. Moreover, although not quantified, the activity of bacteria and fungi also appears to have been stimulated by these solid residues. In such a scenario, it is not surprising to observe a higher accumulation of dry matter and nutrients in plants, particularly phosphorus, with increases ranging from 181 to 1238%, and nitrogen, with increases ranging from 128 to 1621%, not to mention potassium, with increases ranging from 121 to 1527%.

Soil biology, in addition to seemingly affecting the dissolution of gypsum boards powder, eggshells, and the mineralization of Brazilwood leaves, also appears to have played a role in soil pedogenesis. This has promoted better aeration, storage, and circulation of water in the soil (Lopes et al., 2023), working synergistically with calcium.

5. Conclusion

The data indicate that fertilization with gypsum boards powder, eggshells, and green manure from Brazilwood leaves improves the chemical, biological, and physical conditions of the soil. This fertilization stimulates tomato plants to produce sulfur-rich compounds that protect both the roots and the aerial parts from oxidative stress, resulting in excellent performance in water and nutrient absorption and carbohydrate production. This is evidenced by the greater number of leaves, larger stem diameter, and higher accumulation of dry matter and nutrients observed in treatments with additional calcium, particularly at the 800 kg ha^{-1} gypsum dose, which shows increases of over 1238% in nutrient content and biomass in the aerial parts. These results were obtained under field experimental conditions in the northeastern semi-arid region, focusing on family farmers in the Araripe Gypsum Pole.

However, it is necessary to examine, in tomato plants supplemented with gypsum powder, the sulfur-rich secondary metabolites that would be involved in the plant's defense against biotic stress. Furthermore, the real contribution of the oxalate-carbonate pathway and sulfide oxidation to soil pH regulation should be demonstrated.

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References

Araujo, S. M. S. d. *O polo Gesseiro do Araripe: unidades geo-ambientais e impactos da mineração*. [Tese (Doutorado em Ciências), Instituto de Geociencias - Universidade Estadual de Campinas], Campinas, SP, 2004.

Barbosa, A., Ferraz, A., & Santos, G. (2014). Caracterização química, mecânica e morfológica do gesso obtido do pólo do Araripe. *Cerâmica, 60* (356), 501-508. https://doi.org/10.1590/S0366-69132014000400007

Benning, C. (1998). Biosynthesis and function of the sulfolipid sulfoquinovosyl diacylglycerol. *Annual Review of Plant Biology, 49*(49,), 53-75. https://doi.org/https://doi.org/10.1146/annurev.arplant.49.1.53

Bento, J. M. S., Moraes, G. J. d., Matos, A. P. d., Warumby, J. F., & Bellotti, A. C. (2002). Controle biológico da cochonilha da mandioca no nordeste do Brasil. In *Controle biológico no Brasil : parasitóides e predadores*. Manole.

Cakmak, I., & Marschner, H. (1992). Magnesium deficiency and high light intensity enhance activities of superoxide dismutase, ascorbate peroxidase, and glutathione reductase in bean leaves. *Plant Physiol*, *98* (4), 1222-1227. https://doi.org/10.1104/pp.98.4.1222

Cavalcanti, F. J. d. A. *Recomendações de adubação para o Estado de Pernambuco* (Vol. 2). Empresa Pernambucana de Pesquisa Agropecuária-IPA, Recife-PE, 2008.

Damasceno, M. L. *Análise da biomassa florestal do polo gesseiro da Região do Araripe–Pernambuco a partir de índices de vegetação*. [Dissertação (Mestrado em Ciências Geodésicas e Tecnologias da Geoinformação), Departamento de Engenharia Cartográfica, Universidade Federal de Pernambuco - UFPE], Recife, PE, Brasil, 2020.

de Sousa, D. M. G., Rein, T. A., & Albrech, J. C. (2008). *Resposta a gesso pela cultura do algodão cultivado em sistema de plantio direto em um latossolo de cerrado* IX Simpósio Nacional Cerrdos, Planaltina, DF.

de Sousa, D. M. G., Vilela, L., Lobato, E., & Soares, W. V. (2001). *Uso de gesso, calcário e adubos para pastagens no cerrado*. Planaltina, DF: Embrapa Cerrados.

Dedourge, O., Vong, P.-C., Lasserre-Joulin, F., Benizri, E., & Guckert, A. (2004). Effects of glucose and rhizodeposits (with or without cysteine-S) on immobilized-35S, microbial biomass-35S and arylsulphatase activity in a calcareous and an acid brown soil. *European Journal of Soil Science*, *55* (4), 649-656. https://doi.org/https://doi.org/10.1111/j.1365-2389.2004.00645.x

Dekok, L. J. (1993). Role of glutathione in plants under oxidative stress. In L. J. DeKok, Stulen, H. Rennenberg, C. Brunold, & W. E. Rauser (Eds.), *Sulfur nutrition and assimilation in higher plants* (pp. 125-138). SPB ACADEMIC PUBL BV.

EMBRAPA. *Sistema brasileiro de classificação de solos* (5a ed.). Empresa Brasileira de Pesquisa Agropecuária, Brasília, DF, 2018.

Erdei, L., Stuiver, B., & Kuiper, P. J. (1980). The effect of salinity on lipid composition and on activity of Ca2+-and Mg2+-stimulated ATPases in salt-sensitive and salt-tolerant Plantago species. *Physiologia Plantarum*, *49* (3), 315-319.

Ghani, A., McLaren, R. G., & Swift, R. S. (1993). The incorporation and transformations of 35S in soil: Effects of soil conditioning and glucose or sulphate additions. *Soil Biology and Biochemistry*, *25* (3), 327-335. https://doi.org/https://doi.org/10.1016/0038-0717(93)90131-T

Höglund, A. S., Lenman, M., Falk, A., & Rask, L. (1991). Distribution of myrosinase in rapeseed tissues. *Plant Physiol*, *95*(1), 213-221. https://doi.org/10.1104/pp.95.1.213

IBGE-SIDRA. (2021). *Levantamento sistemático da produção agrícola*. Instituto Brasileiro de Geografia e Estatística. https://sidra.ibge.gov.br/home/lspa/brasil

Jennings, D. H. *The Physiology of Fungal Nutrition*. Cambridge University Press, Cambridge, 1995. 9780521355247.

Jones, D. A., & Takemoto, D. (2004). Plant innate immunity – direct and indirect recognition of general and specific pathogen-associated molecules. *Current Opinion in Immunology*, *16* (1), 48-62. https://doi.org/https://doi.org/10.1016/j.coi.2003.11.016

Ker, J. C., Curi, N., Schaefer, C. E. G. R., & Vidal-Torrado, P. (2015). Pedologia: fundamentos.

Lepsch, I. F. *19 lições de pedologia* (2a ed.). Oficina de textos, São Paulo, SP, Brasil, 310p, 2021.

Levitt, J. *Responses of plants to environmental stresses* (2a ed.). Academic Press, New York, 1980. 0124455018.

Liang, Q., Chen, L., Yang, X., Yang, H., Liu, S., Kou, K., & Yuan, Y. (2022). Natural variation of Dt2 determines branching in soybean. *Nature Communications*, *13* (1), 6429. https://doi.org/10.1038/s41467-022-34153-4

Lopes, D. I., Vergara, C., Araujo, K. E. C., & Saraiva, E. C. (2023). Uso da mucuna-preta e vermicomposto como adubo orgânico de alface em Moçambique. *Research, Society and Development*, *12* (2), e17512240017. https://doi.org/10.33448/rsd-v12i2.40017

Marschner, H. *Marschner's mineral nutrition of higher plants* (Third ed.). Academic press, Elsevier, 2011. 0123849063.

Martin, G., Guggiari, M., Bravo, D., Zopfi, J., Cailleau, G., Aragno, M., & Unier, P. (2012). Fungi, bacteria and soil pH: the oxalate–carbonate pathway as a model for metabolic interaction. *Environmental Microbiology*, *14* (11), 2960-2970. https://doi.org/https://doi.org/10.1111/j.1462-2920.2012.02862.x

McCully, M. E., Miller, C., Sprague, S. J., Huang, C. X., & Kirkegaard, J. A. (2008). Distribution of glucosinolates and sulphur-rich cells in roots of field-grown canola (Brassica napus). *New Phytologist*, *180* (1), 193-205. https://doi.org/https://doi.org/10.1111/j.1469-8137.2008.02520.x

Neto, C. d. M. e. S., Carneiro, V. A., Ribeiro, A. C. C., de Oliveira, T. M., & Gonçalves, B. B. (2015). Utilização de resíduos de gesso da construção civil para incremento no desenvolvimento de crotalaria retusa. *Brazilian Geographical Journal*, *6*, 140.

Nieto-Sotelo, J., & Ho, T.-H. D. (1986). Effect of Heat Shock on the Metabolism of Glutathione in Maize Roots 1. *Plant physiology*, *82* (4), 1031-1035. https://doi.org/10.1104/pp.82.4.1031

Novais, R. F., V., V. H. A., Barros, N. F. d., Fontes, R. L. F., & Lima, R. B. C. J. C. *Fertilidade do solo*. Sociedade Brasileira de Ciência do Solo, Viçosa, Minas Gerais, 2007. 978-85-86504-08-2.

Paul, E., & Frey, S. *Soil microbiology, ecology and biochemistry*. Elsevier, 2023. 0128234156.

Pereira, A. S., Shitsuka, D., Parreira, F., & Shitsuka, R. *Metodologia da pesquisa científica [recurso eletrônico]* (1 ed.). UFSM, NTE, Santa Maria, RS, Brasil, 2018. 978-85-8341-204-5.

Rennenberg, H., & Lamoureux, G. L. (1990). Physiological processes that modulate the concentration of glutathione in plant cells. In *Sulfur nutrition and sulfur assimilation in higher plants: regulatory agricultural and environmental aspects* (pp. 53-65). SPB Academic Publishing bv.

Rivero, R. M., Mittler, R., Blumwald, E., & Zandalinas, S. I. (2022). Developing climate-resilient crops: improving plant tolerance to stress combination. *The Plant Journal*, *109* (2), 373-389. https://doi.org/https://doi.org/10.1111/tpj.15483

Salino, R. E., Nagalli, A., de Campos, R. F. F., & Catai, R. E. (2021). Resíduos de gesso de construção: geração e reciclagem: construction plaster waste: generation and recycling. *IGNIS: Periódico Científico de Arquitetura e Urbanismo Engenharias e Tecnologia de Informação*, *10* (2), 51-67.

Santos, P. M. d., Rolim, M. M., Duarte, A. d. S., Barros, M. d. F. C., & Silva, Ê. F. d. F. e. (2014). Uso de resíduos de gesso como corretivo em solo salino-sódico. *Tropical agricultural research*, *44* (1), 95-103. https://doi.org/https://doi.org/10.1590/S1983-40632014000100004

Schmalenberger, A., Hodge, S., Bryant, A., Hawkesford, M. J., Singh, B. K., & Kertesz, M. A. (2008). The role of Variovorax and other Comamonadaceae in sulfur transformations by microbial wheat rhizosphere communities exposed to different sulfur fertilization regimes. *Environmental Microbiology*, *10* (6), 1486-1500. https://doi.org/https://doi.org/10.1111/j.1462-2920.2007.01564.x

Schmalenberger, A., Hodge, S., Hawkesford, M. J., & Kertesz, M. A. (2009). Sulfonate desulfurization in Rhodococcus from wheat rhizosphere communities. *FEMS Microbiology Ecology*, *67* (1), 140-150. https://doi.org/10.1111/j.1574-6941.2008.00602.x

Schmalenberger, A., Telford, A., & Kertesz, M. A. (2010). Sulfate treatment affects desulfonating bacterial community structures in Agrostis rhizospheres as revealed by functional gene analysis based on asfA. *European Journal of Soil Biology*, *46* (3), 248-254. https://doi.org/https://doi.org/10.1016/j.ejsobi.2010.03.003

Schnug, E. (1993). Physiological functions and environmental relevance of sulfur-containing secondary metabolites. In (pp. 179-190).

Schurmann, P. (1993). Plant thioredoxins. In *Sulfur nutrition and sulfur assimilation in higher plants: regulatory agricultural and environmental aspects* (pp. 153-162). SPB Acad.

SDT/MDA. (2015). *Perfil Territorial*. SDT - Secretaria de Desenvolvimento Territorial/MDA – Ministério de Desenvolvimento Agrário. http://sit.mda.gov.br/download/caderno/caderno_territorial_081_Sert%C3%83%C2%A3o%20do%20Araripe%20-%20PE.pdf

Silva, J., Dutra, A., Cavalcanti, N., Melo, A., Gonçalves, F., & Silva, J. (2014). Aspectos agronômicos do tomateiro “Caline Ipa 6” cultivado sob regimes hídricos em área do semiárido. *Revista Agro@mbiente On-line*, *8*, 336-344. https://doi.org/10.5327/Z1942-847020140001951

Sposito, G. *The chemistry of soils*. Oxford university press, 2008. 0195313690.

Stuiver, C. E. E., Kuiper, P. J. C., & Marschner, H. (1978). Lipids from Bean, Barley and Sugar Beet in Relation to Salt Resistance. *Physiologia Plantarum*, *42* (1), 124-128. https://doi.org/https://doi.org/10.1111/j.1399-3054.1978.tb01551.x

Taiz, L., Zeiger, E., Møller, I. M., & Murphy, A. *Fisiologia e Desenvolvimento Vegetal* (6 ed.). Artmed Editora, Porto Alegre, RS, Brasil, 2016.

Team, R. C. (2023). *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/

Tomati, U., & Galli, E. (1979). Water Stress and —SH-Dependent Physiological Activities in Young Maize Plants. *Journal of Experimental Botany*, *30* (3), 557-563. https://doi.org/10.1093/jxb/30.3.557

Vergara, C., & Araujo, K. E. C. (2024). Arbuscular Mycorrhizal Symbiosis: From Infection Signaling to Bidirectional Nutrient Exchanges. In M. Parihar, A. Rakshit, A. Adholeya, & Y. Chen (Eds.), *Arbuscular Mycorrhizal Fungi in Sustainable Agriculture: Inoculum Production and Application* (pp. 401-418). Springer Nature Singapore. https://doi.org/10.1007/978-981-97-0296-1_18

Vergara, C., Araujo, K. E. C., Santos, A. P., Oliveira, F. F. d., Silva, G. d. S., Miranda, N. d. O., & Medeiros, J. F. d. (2024). Use of crushed eggshell to control tomato blossom-end rot. *Research, Society and Development*, *13* (5), e2213545667. https://doi.org/10.33448/rsd-v13i5.45667

Vergara, C., Araujo, K. E. C., Souza, S. R. d., Schultz, N., Saggin, O. J., Sperandio, M. V. L., & Zilli, J. É. (2019). Plant-mycorrhizal fungi interaction and response to inoculation with different growth-promoting fungi. *Pesquisa Agropecuária Brasileira*, *54*, e25140. https://doi.org/https://doi.org/10.1590/S1678-3921.pab2019.v54.25140

Vergara, C., Araujo, K. E. C., Sperandio, M. V. L., Santos, L. A., Urquiaga, S., & Zilli, J. É. (2019). Dark septate endophytic fungi increase the activity of proton pumps, efficiency of 15 N recovery from ammonium sulphate, N content, and micronutrient levels in rice plants. *Brazilian Journal of Microbiology*, *50*, 825-838. https://doi.org/https://doi.org/10.1007/s42770-019-00092-4

Vergara, C., Araujo, K. E. C., Urquiaga, S., Santa-Catarina, C., Schultz, N., da Silva Araújo, E., & Zilli, J. É. (2018). Dark Septate Endophytic Fungi Increase Green Manure-(15)N Recovery Efficiency, N Contents, and Micronutrients in Rice Grains. *Frontiers in Plant Science*, *9*, 613. https://doi.org/10.3389/fpls.2018.00613

Vergara, C., Araujo, K. E. C., Urquiaga, S., Schultz, N., Balieiro, F. d. C., Medeiros, P. S., & Zilli, J. E. (2017). Dark Septate Endophytic Fungi Help Tomato to Acquire Nutrients from Ground Plant Material [Original Research]. *Frontiers in Microbiology*, *8* (2437). https://doi.org/10.3389/fmicb.2017.02437

Vergara, C., Araujo, K. E. C., & Zilli, J. É. (2023). Physiological changes in tomato colonized by dark septate endophytic fungi. *Research, Society and Development*, *12* (4), e28712441188-e28712441188. https://doi.org/https://doi.org/10.33448/rsd-v12i4.41188

Vong, P.-C., Dedourge, O., Lasserre-Joulin, F., & Guckert, A. (2003). Immobilized-S, microbial biomass-S and soil arylsulfatase activity in the rhizosphere soil of rape and barley as affected by labile substrate C and N additions. *Soil Biology and Biochemistry*, *35*(12), 1651-1661. https://doi.org/https://doi.org/10.1016/j.soilbio.2003.08.012

Wink, M. (1993). The Plant Vacuole: A Multifunctional Compartment. *Journal of Experimental Botany*, *44*, 231-246. http://www.jstor.org/stable/23694159

WRB/FAO. *World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports Nº. 106*. FAO, Rome, 2015. 978-92-5-108369-7.

Yang, Z.-H., StÖVen, K., Haneklaus, S., Singh, B. R., & Schnug, E. (2010). Elemental Sulfur Oxidation by Thiobacillus spp. and Aerobic Heterotrophic Sulfur-Oxidizing Bacteria. *Pedosphere*, *20* (1), 71-79. https://doi.org/https://doi.org/10.1016/S1002-0160(09)60284-8