UFSM

Ciência Florestal

ISSN 1980-5098
OPEN ACCESS

Ci. Fl., Santa Maria, v. 34, n. 2, e68293, p. 1-19, Apr./June 2024 • https://doi.org/10.5902/1980509868293
Submitted: 28th/10/2021 • Approved: 30th/11/2023 • Published: 7th/06/2024

Articles

Organomineral fertilizers and soil remineralizer in the initial growth of mycorrhized *Eucalyptus grandis* W. Hill ex Maiden

Fertilizantes organomineral e remineralizador do solo no crescimento inicial de *Eucalyptus grandis* W. Hill ex Maiden micorrizado

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ABSTRACT

The post-planting growth of eucalyptus requires proper fertilization to provide nutrients in adequate amounts for the seedlings. This study aimed to determine the contribution of organomineral fertilizers and soil remineralizers to the initial growth of mycorrhized *Eucalyptus grandis*. The experiment was conducted in a greenhouse at the Federal University of Santa Maria, Frederico Westphalen campus. The experimental design was completely randomized in a factorial arrangement (2x6), combined or not with inoculation of the ectomycorrhizal fungus *Pisolithus microcarpus* and six fertilizers (mineral fertilizer, mineral fertilizer with remineralizer, organomineral fertilizer, with two levels of phosphorus content — high and low), with five repetitions. After ninety days of cultivation, the height, stem diameter, number of leaves, dry mass of aerial parts, root dry mass, total dry mass, root volume, height/stem diameter ratio, Dickson Quality Index, relative growth efficiency index, and mycorrhizal colonization were evaluated. The results were submitted to analysis of variance and the means compared using Tukey's test. The results showed that the organomineral fertilizer increased the morphological parameters and quality of *Eucalyptus grandis*, with the seedlings achieving greater mycorrhizal colonization in treatments with the remineralizer or organic fertilizer in the composition with the mineral fertilizer.

Keywords: Eucalyptus; Ectomycorrhization; *Pisolithus microcarpus*; Swine wastewater

RESUMO

O crescimento pós-plantio do eucalipto requer correta adubação, a fim de disponibilizar nutrientes em quantidade adequada para as mudas. O trabalho objetivou determinar a contribuição de fertilizantes organomineral e de remineralizadores do solo no crescimento inicial de *Eucalyptus grandis* micorrizado. O experimento foi conduzido em casa de vegetação da Universidade Federal de Santa Maria, campus de Frederico Westphalen. O delineamento experimental foi inteiramente casualizado em arranjo fatorial (2x6), combinado ou não com inoculação do fungo ectomicorrízico *Pisolithus microcarpus* e seis fertilizantes (fertilizante mineral, fertilizante mineral com remineralizador, fertilizante organomineral, com dois níveis de fósforo – com alto e baixo teor de fósforo), com cinco repetições. Decorridos noventa dias de cultivo, foi avaliada a altura, diâmetro de colo, número de folhas, massa seca da parte aérea, massa seca da raiz, massa seca total, volume radicular, relação altura/diâmetro de colo, Índice de Qualidade de Dickson, índice de eficiência relativa no crescimento e colonização micorrízica. Os resultados foram submetidos à análise de variância e as médias comparadas pelo teste de Tukey. O fertilizante organomineral possibilita incremento nos parâmetros morfológicos e qualidade do *Eucalyptus grandis*, as mudas obtiveram maior colonização micorrízica nos tratamentos com adição de remineralizador ou fertilizante orgânico na composição com o fertilizante mineral.

Palavras-chave: Eucalipto; Ectomicorrização; *Pisolithus microcarpus*; Água residuária de suinocultura

1 INTRODUCTION

Eucalyptus grandis W. Hill ex Maiden, a member of the Myrtaceae family, is the primary tree species used in reforestation in Brazil, accounting for 76.2% of the area of planted forests, approximately 7.5 million hectares (IBGE, 2018). It adapts well to low-fertility soils, thus being recommended for moist and well-drained soils, facilitating its use as a source of income in reforested areas (Schumacher *et al*., 2005). Nevertheless, for obtaining quality plants with good growth, the appropriate availability of nutrients during their production is notably significant, with phosphorus being a growth and quality limiter for the seedlings (Rocha *et al*., 2013).

In this context, post-composting, the solid fraction of swine manure shows a higher proportion of phosphorus relative to nitrogen and potassium (Orrico Júnior; Orrico; Lucas Júnior, 2009). Using this composted waste as organic fertilizer provides forest seedlings with increases in height, stem diameter, root, and total dry mass, improves height/diameter ratio (Oliveira *et al*., 2008; Lanna *et al*., 2017), and also enhances nutrient absorption compared to mineral fertilizer (Lanna *et al*., 2017).

Soil remineralizers emerge as an alternative nutritional source for crops, acting as soil restorers for degraded soils and providing increments in agricultural and forestry productivity (MAPA, 2016; Theodoro *et al*., 2013; Silva *et al*., 2012). These are mineral-origin products, resulting from the reduction and classification by mechanical processes of rock, capable of adding and making macro and micronutrients available to plant systems, improving the soil's physicochemical properties and biological activity (Brasil, 2013). Evidence has shown the economic, agronomic, and forestry importance of this input, as it enables one to achieve productivity comparable to chemical fertilizers (Tavares *et al*., 2018; Pereira *et al*., 2012; Souza *et al*., 2019; Silva *et al*., 2012). Its use also allows higher concentrations of potassium and silicon in *E. benthamii* Maiden et Cambage leaves than conventional fertilization and increases soil pH (Silva *et al*., 2012). Thus, combining organomineral fertilizers with soil remineralizers offers a nutritionally advantageous alternative in eucalyptus cultivation.

In addition to fertilizers, ectomycorrhizas can benefit eucalyptus cultivation by stimulating its initial growth. This association enables the roots to absorb more nutrients and water due to the formation of structures such as the Hartig net, expanding the root absorption area (Brundrett *et al*., 2008). In this regard, researchers have shown that *E. grandis* establishes ectomycorrhizas, consequently increasing its nutrient absorption capacity, root area, and aerial part, which provide better adaptation to adverse conditions and post-planting establishment success (Gómez; Rodriguez, 2012; Weirich *et al*., 2018), as well as superior growth conditions and seedling quality (Andreazza *et al*., 2004). Additionally, inoculation with *Pisolithus microcarpus* enhances survival conditions, height, diameter, and nutrient content in the aerial part (Mello *et al*., 2009).

The use of alternative fertilizers for plants, through organic waste and remineralizers, may be an alternative to mixing with mineral fertilizers. However, the performance of these fertilizers in fast-growing forest species with nutritional demands (e.g., eucalyptus) still requires further research. Therefore, this study aimed to evaluate the use of organic fertilizer and soil remineralizer associated with mineral fertilizer in the initial growth of mycorrhized *E. grandis*.

2 MATERIALS AND METHODS

The experiment was carried out between January and April 2019 in a greenhouse at the Federal University of Santa Maria (Frederico Westphalen campus), Rio Grande do Sul, southern Brazil (27°23'26" S, 53°25'43" W; 461.30 m altitude). A red latosol was used (Santos, 2018); it was collected from an agricultural production area in the 0–20 cm layer, with a clay texture of 70%. To achieve a 35% clay content, medium sand was mixed in a 50% (v/v) ratio to facilitate root cleaning. Subsequently, dolomitic limestone (PRNT 100%) was added to raise the base saturation to 40%, as recommended for eucalyptus cultivation (CQFS, 2016). The experimental units were maintained in a greenhouse under an automatic misting system with a 7 mm water layer for 30 days to stabilize the soil's physicochemical properties. The soil texture determination and chemical analyses were conducted according to EMBRAPA (2017) and described in Table 1.

Table 1 – Physicochemical analysis of the original soil and its mixture with medium sand

Soil	Clay* %	pH_{water} 1:1	MO %	P	K	Ca	Mg	Al+H	Base saturation	Al saturation
				mg dm^{-3}		$Cmol_c$ dm^{-3}			%	
100%	70	5.3	1.10	6.50	26.50	0.40	0.10	3.30	23	37
Soil + sand[1]	34	6.7	0.52	4.50	21.60	1.40	0.56	3.00	40.1	0

Source: Authors (2023)

In where: Chemical characterization after soil correction with dolomitic limestone (PRNT 100%). *The clay content was determined using the pipette method, as per Embrapa (2017).

The experimental design was completely randomized in a 2 x 6 factorial arrangement (AxD), with the "A" factor levels being qualitative for inoculation (with and without ectomycorrhiza) and the "D" factor levels also qualitative, composed of six forms of fertilization: mineral fertilizer (MF), mineral fertilizer with remineralizer (MF+REM), organomineral fertilizer (OMF) — the organic fertilizer with mineral adjustment, with two levels of phosphorus in the formulations (high and low phosphorus content), with five repetitions.

The mineral fertilizer comprised urea, triple superphosphate, and potassium chloride. The OMF was made by mixing mineral fertilizers with organic fertilizer granules. The organic fertilizer, in turn, came from the Swine Wastewater Treatment System (Sistars) installed in the swine sector of the university (system submitted for patent registration). The solid fraction separated by decantation and after dewatering and the solid fraction separated by screening were composted together for 45 days. After this period, the composted fraction was sieved and submitted to granulation (granulation process submitted for patent registration).

The mineral fertilizer + soil remineralizer was obtained by mixing granules of mineral fertilizers with remineralizer powder. The soil remineralizer was acquired from Alessi Mineração (Frederico Westphalen, RS), obtained by screening process (0.6 mm mesh), resulting from the crushing of basaltic rocks. The formulations and components used to manufacture the fertilizers are listed in Table 2.

Treatments with MF received a dose of 722.22 kg/ha, and treatments using MF + REM and OMF received a dose of 1444.46 kg/ha, according to the recommendations of the Soil Chemistry and Fertility Commission for a population of 10,000 eucalyptus plants per hectare (CQFS, 2016).

Table 2 – List of fertilizers used in the treatments with fertilization

Fertilizer	P content	Formulation			Components
		N	P_2O_5	K_2O	
MF	Low	6	4	18	Urea + triple super phosphate + potassium chloride
	High	6	18	18	
MF + REM	Low	3	2	9	Urea + triple super phosphate + potassium chloride + basalt powder (remineralizer)
	High	3	9	9	
OMF	Low	3	2	9	Urea + triple super phosphate + potassium chloride + solid fraction of pig manure
	High	3	9	9	

Source: Authors (2023)

In where: MF = mineral fertilizer; MF + REM = mineral fertilizer + remineralizer; OMF = organomineral fertilizer.

E. grandis seeds were provided by the Santa Maria Forest Research Center (FEPAGRO, RS). Before sowing, they were disinfected with a 5% (v/v) commercial

sodium hypochlorite solution for 20 minutes and rinsed under running water for 5 minutes, then sown in polystyrene trays with 15.5 mL cells in Carolina Soil® commercial substrate, previously sterilized in an autoclave at 121°C in 3 cycles of 30 minutes. After sowing, the trays were kept under manual irrigation with distilled water to maintain 70% field capacity moisture. When the seedlings had a pair of true leaves, thinning was performed, leaving one plant per cell of the tray.

When the seedlings reached four pairs of true leaves (about 10 cm), they were transplanted into 5-L polyethylene pots, with 5 kg of soil previously sterilized in an autoclave at 121°C in three cycles of 30 minutes. Each pot with a plant comprised an experimental unit. Fertilizers were incorporated into the potting soil the day before transplanting the seedlings, and the amount of fertilizer used was according to the recommendations of the CQFS manual (2016) for a population of 10,000 eucalyptus plants per hectare.

Inoculation was carried out at the time of seedling transplant with the ectomycorrhizal fungus *P. microcarpus*, obtained from the fungal bank of the Department of Soils of the Federal University of Santa Maria. The inoculant preparation was performed by blending fungal colonies in a blender with 500 mL of distilled water for 10 seconds. The colonies were grown on 7 Petri dishes in Modified Melin-Nokrans Medium (MNM) for 30 days in an Incubation Chamber at 25°C. For inoculation, 10 mL of this solution was applied with a graduated syringe adjacent to the root system of the seedlings. Treatments without inoculation also received 10 mL of a solution containing only the MNM culture medium.

Irrigation was carried out daily using the greenhouse's automatic misting system, with a 7 mm water layer. Preventive phytosanitary management was carried out every 21 days with the application of pyrethroid insecticides, ensuring no occurrence of insects and diseases during the experiment. The experimental units were rotated weekly to meet the experimental design requirements.

At the end of the experiment (90 days after transplanting), the height of the aerial part was evaluated, determined with a millimeter ruler from the plant's collar to the insertion of the last leaf, and the stem diameter, measured with a digital caliper at the plant's collar region. The root volume was determined by the water displacement method in a graduated cylinder, adapted from the methodology used in soils by Embrapa (2017). The dry mass of the aerial part (DMAP) and roots (DRM) were determined by separating these parts at the plant's collar and drying them in an oven at 65±1°C until constant mass. The total dry mass (TDM) was obtained from the sum of DRM and DMAP. The H/D and H/DMAP ratios were determined from the division between the height and the stem diameter of the seedling and between the height and the dry mass of the aerial part, respectively.

The Dickson Quality Index (DQI) was determined based on the height of the aerial part (H), stem diameter (SD), dry mass of the aerial part DMAP, and DRM, using Equation (1):

$$DQI = \frac{TDM(g)}{\big(H(cm)SD(cm)\big) + \left(\frac{DMAP(g)}{DRM(g)}\right)} \quad (1)$$

The percentage of mycorrhizal colonization was determined using the technique of root clarification and staining with 0.05% Trypan blue for visualization under an optical microscope and magnifying glass of the fungal mantle, formed by the ectomycorrhiza, with five repetitions per plant, estimated by the gridline intersect method (Brundrett *et al.*, 2008), according to the formula: mycorrhizal colonization (%) = (total number of colonized roots/total number of roots) * 100.

The calculation of the relative efficiency index (REI) was used to compare the efficiency of fertilizers regarding biomass production (total dry mass) and calculated using Equation (2) and the mineral fertilizer with low P content (NPK formula 6-4-18) as control:

$$REI = \frac{TDMFertilizer(X) - TDMFertilizer(6-4-18)}{TDMFertilizer(6-4-18)} x100 \quad (2)$$

The results were submitted to the Shapiro-Wilk test to determine the normality of the collected data. Subsequently, an analysis of variance was performed, and when there was significant interaction, the inoculum variation factor was unfolded within the fertilizer factor, and when it was not significant, the simple effects of each variation factor were unfolded. The means were compared using the Tukey test at 5% significance and the SISVAR Software (Ferreira, 2014).

3 RESULTS AND DISCUSSIONS

The results showed a significant interaction between inoculum and type of fertilizer in the DRM and the H/DMAP ratio of eucalyptus seedlings, while for other variables, there was no significant interaction between factors, only a significant simple effect for fertilizer. The H/D ratio did not show significant interaction or simple effects.

The DRM was significantly higher in the treatment with the addition of OMF without mycorrhiza, regardless of phosphorus content, and with mycorrhizal inoculation in the organomineral treatment with high phosphorus (Table 3). This occurs due to the decrease in carbon allocation for root tissue production caused by mycorrhizal colonization, reducing plant root biomass (Vandresen *et al*., 2007). However, even though inoculation reduces the root system, there is an increase in the root absorption area due to the presence of fungal hyphae in the roots (Brundrett, 2008), which consequently increases the growth capacity of plants in degraded soils with low nutrient availability (Bertolazi *et al*., 2010). Knowledge of root system data is of fundamental importance due to its correlation with the survival and initial growth of seedlings, as roots primarily function to absorb water and nutrients from the soil after planting (Andreazza *et al*., 2004; Oliveira *et al*., 2008; Weirich *et al*., 2018). The results indicate that organomineral fertilizer stimulates the production of root mass.

The H/DMAP ratio showed significant interaction, varying according to inoculation and the fertilizer used, being lower with OMF regardless of inoculation (Table 3). In treatments without inoculation, the mineral fertilizer + remineralizer with

high P content had the highest value, not differing from the exclusive use of mineral fertilizer with high and low phosphorus. When inoculated, the mineral fertilizer with low phosphorus content was higher, not differing from the remineralizers, while the lowest averages for the H/DMAP ratio were observed. The lower the value of this ratio, the better the quality of the plant, as higher than recommended values indicate less lignification of the seedlings and, thus, lower post-planting survival capacity (Da Ros *et al*., 2018). Thus, the results infer that OMF induces a better H/DMAP ratio.

Table 3 – Dry root mass (DRM) and the ratio of height to dry mass of the aerial part (H/DMAP) of *Eucalyptus grandis* subjected to ectomycorrhizal inoculation (without and with) grown in soil with different fertilizers with low and high phosphorus content

Fertilizer	DRM (g)				Ratio H/DMAP			
	Without		With		Without		With	
Mineral Fertilizer — low P	3.60	bA	3.13	cA	8.71	abA	10.62	aA
Mineral Fertilizer — high P	5.32	bA	4.74	cA	10.03	abA	6.89	bB
MF + REM — low P	4.43	bA	3.57	cA	8.07	bA	8.98	abA
MF + REM — high P	2.93	bB	5.39	cA	11.27	aA	7.82	abB
OMF — low P	14.12	aA	9.44	bB	3.51	cA	2.96	cA
OMF — high P	14.57	aA	14.64	aA	2.88	cA	2.89	cA

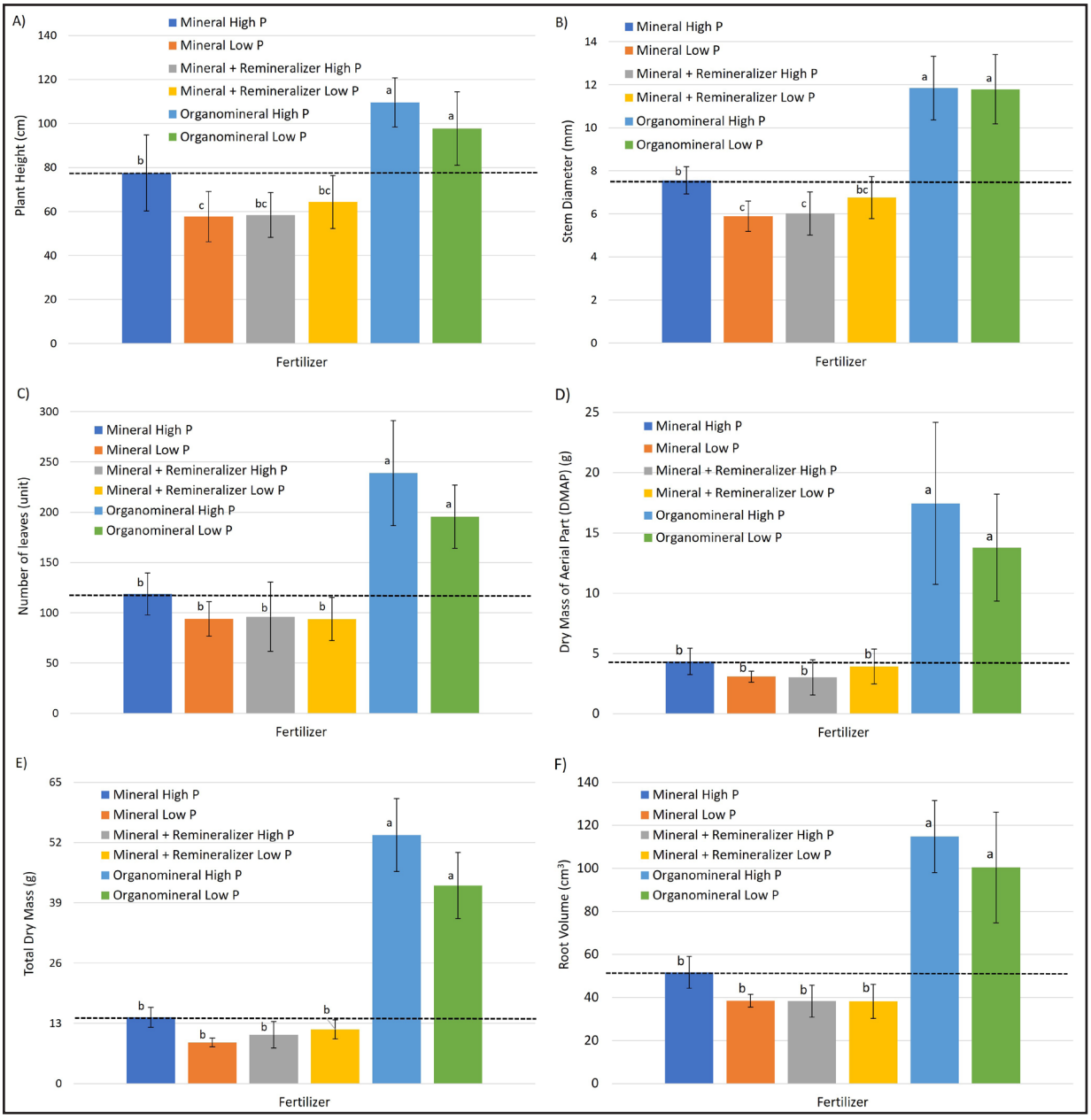
Source: Authors (2023)

In wheew: MF = mineral fertilizer; MF + REM = mineral fertilizer + remineralizer; OMF = organomineral fertilizer. Means followed by the same lowercase letter in the column and uppercase in the row do not differ by the Tukey test ($p \leq 0.05$).

There was no interaction, only a significant simple effect of fertilizer on height, stem diameter, number of leaves, dry mass of the aerial part, total dry mass, and root volume of eucalyptus (Figure 1). The OMF allowed for greater height and diameter, regardless of phosphorus content (Figure 1A, 1B). The literature reports that the use of swine wastewater, a product with a lower concentration of phosphorus and nitrogen compared to its solid part (Orrico Júnior; Orrico; Lucas Júnior, 2009), results in greater height and diameter of *E. grandis* compared to the control, irrigated with water (Pelissari *et al*., 2009). In native species, such as the soursop tree (*Annona muricata* L. 'Morada'), the use of vermicompost and animal waste as organic fertilizer allows for significant increases in height, diameter, and dry mass of the aerial part (Eckhardt *et*

al., 2021). Figueiredo *et al*. (2019) comment that plants with greater heights represent favorable field conditions due to the greater potential for root development, providing rapid establishment and resulting in greater growth in height.

Figure 1 – Simple effect of mineral fertilizer associated with remineralizer and organic fertilizer with high and low P content of eucalyptus seedlings



Source: Authors (2023)

In where: plant height (A); stem diameter (B); number of leaves (C); dry mass of the aerial part (D); total dry mass (E); root volume (F); Means followed by the same lowercase letter do not differ from each other by the Tukey test ($p \leq 0.05$).

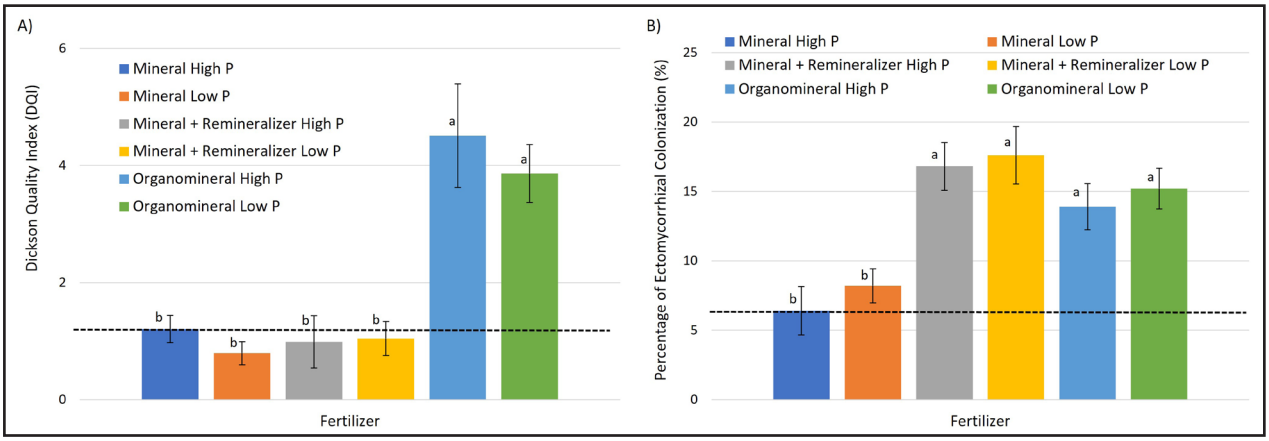
Regarding the number of leaves (Figure 1C) and dry mass of the aerial part (Figure 1D), it was evident that treatments under fertilization with organominerals were significantly greater than the others. The influence of OMF found in this work corroborates the results of Eckhardt (2021), where the use of animal waste as fertilizers significantly increased the dry mass of the aerial part of eucalyptus compared to the use of the commercial substrate. The literature reports that the use of organic compounds provides plants with a leaf increment superior to those under commercial substrate (Plantmax®) (Pereira *et al*., 2012). The importance of this analysis lies in the direct relationship that the number of leaves has with the leaf area of the seedlings, which correlates positively with the growth of eucalyptus in the field as it provides greater photosynthetic capacity (Figueiredo *et al*., 2019).

Total dry mass was also significantly higher with the OMF compared to the others, which, in turn, did not differ from each other (Figure 1E). The influence of the use of organic materials on plant dry biomass was also verified in other studies. Chicory plants subjected to fertilization with Provaso® organic compost showed a superior increase in total dry mass compared to mineral fertilization (Lanna *et al*., 2017). *E. grandis* had its aerial and root dry mass positively influenced by using animal waste as fertilizer, compared to commercial substrate (Eckhardt *et al*., 2021).

Organomineral fertilizers with high and low phosphorus content also increased the root volume of eucalyptus plants (Figure 1F). Silva *et al*. (2020) observed that organic fertilization, through bovine manure and organomineral, provided increments in the root volume of corn, being respectively, superior and equivalent to mineral fertilization. This result is crucial for a better understanding of the survival and initial growth of seedlings, as roots primarily function to absorb water and nutrients from the soil after planting (Andreazza *et al*., 2004; Oliveira *et al*., 2008; Weirich *et al*., 2018). The results of this study align with those obtained by Oliveira *et al*. (2008), who demonstrated that the use of organic compost provides greater growth of the forest species *Cedrela fissilis* Vell., *E. grandis* W. Hill ex Maiden, *Acacia holocericea* A. Cunn. ex G. Don, and *Schinus terebinthifolius* Raddi.

The DQI was significantly higher with the use of OMF (Figure 2A). Silva *et al*. (2017a) also observed, 60 days after transplant, that the initial development of *E. grandis* was significantly greater with the use of organic compounds based on biochar from sewage sludge and sewage sludge, with higher values of height, stem diameter, dry mass of the aerial part and roots, and DQI. According to the same authors, integrating characteristics, such as height, aerial part and root biomass, and diameter, through the evaluation of DQI, makes the interpretation of quality parameters more appropriate, as this index considers important issues of robustness and the distribution of biomass balance.

Figure 2 – Percentage of mycorrhizal colonization of *Eucalyptus grandis* cultivated with mineral fertilizer, soil remineralizer, and OMF with high and low phosphorus content



Source: Authors (2023)

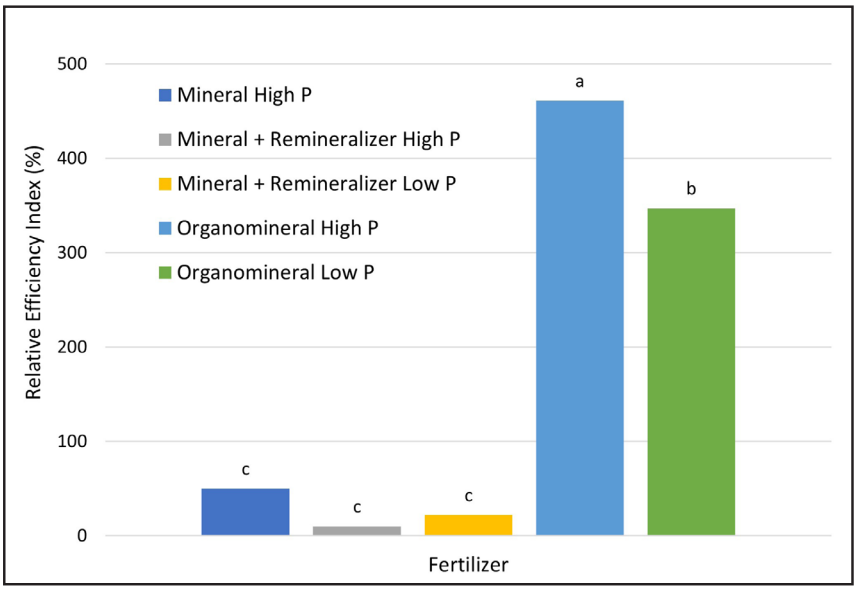
In where: Means followed by the same lowercase letter do not differ from each other by the Tukey test ($p \leq 0.05$).

The percentage of mycorrhizal colonization was significantly higher with the addition of remineralizer and organic fertilizer to the mineral fertilizer, regardless of the phosphorus content (Figure 2B). Organic fertilizer provides a gradual release of nutrients, such as the natural phosphates of the remineralizer, which stimulates the plant's association with the fungus, increasing the root system and the production of enzymes and organic acids that will provide nutrients (Landeweert *et al*., 2001).

Regarding the low mycorrhizal colonization found in treatments with the exclusive use of mineral fertilizer, Grazziotti *et al*. (2003) comment that the high content of nutrients readily available to plants can result in low mycorrhizal association due to the insignificant or non-existent stimulation of symbiotic relationships between fungus and plant. When analyzing the responses of mycorrhizal association in relation to phosphorus levels in the soil, the literature reports that an increase in phosphorus doses applied to the soil reduces fungal colonization, highlighting a negative correlation between phosphorus and mycorrhizal colonization (Silva *et al*., 2016), which was not evidenced in this study.

The Relative Efficiency Index on the total dry mass of eucalyptus revealed that the OMF with high P content (3-9-9), followed by the organomineral with low P content, were superior to the others, being respectively 461 and 347% higher than the control fertilizer (mineral with low P content) (Figure 3). A similar response of OMF on the dry mass of eucalyptus was also observed in the work of Magalhães *et al*. (2017), where the treatment with the use of ruminal content of beef cattle, along with reactive Bayovar natural phosphate, showed an agronomic efficiency index similar to chemical fertilization (magnesian thermophosphate + BASACOT MINI 6M®).

Figure 3 – Relative efficiency index of fertilizers in total dry mass production of *Eucalyptus grandis*



Source: Authors (2023)

In where: Means followed by the same lowercase letter do not differ from each other by the Tukey test ($p \leq 0.05$).

Organomineral fertilizers showed superior values in the evaluated parameters, indicating better nutrient utilization by the plant. This results from the characteristic of slow release of nutrients contained in organic fertilizers compared to mineral fertilizers, as over time there is mineralization and gradual release (Severino *et al*., 2004). While mineral fertilizers with soil remineralizer induced a lower response than organominerals, they were equivalent to the exclusive use of mineral fertilizer for the growth and quality index of eucalyptus. This can be explained by these fertilizers requiring more time for the dissolution of their mineral sources (Silva *et al*., 2017b), constituted by residues from the mining of amethysts and basalt and rock powder (Table 2).

4 CONCLUSIONS

This study highlights the significant potential of alternative fertilizers in producing forest seedlings, emphasizing the crucial role of organomineral fertilizer in promoting improvements in morphological parameters and the quality of *Eucalyptus grandis* seedlings compared to using mineral fertilizers. Autoclaved soil favors the association with ectomycorrhizal fungi, highlighting the need for studies without this experimental control.

A more pronounced ectomycorrhizal colonization was observed in *Eucalyptus grandis* seedlings when remineralizer or organic fertilizer was added to the composition with mineral fertilizer. In addition to offering significant contributions to future studies on the use of alternative fertilizers, this research emphasizes the superiority of these inputs over minerals, underlining their ability to maximize interaction with beneficial microorganisms. These results provide valuable insights for agro-industries and rural producers, offering tangible opportunities to increase efficiency and profitability by effectively utilizing by-products.

It is crucial to conduct more comprehensive studies on the interaction between ectomycorrhizal fungi and *Eucalyptus grandis*, with special emphasis on selecting specific species to optimize benefits for seedlings. This work establishes a solid foundation for ongoing understanding and exploration of the potential of alternative fertilizers in the context of forest production.

ACKNOWLEDGMENTS

The authors kindly thank the Coordination for the Improvement of Higher Education Personnel (CAPES) and the National Council for Scientific and Technological Development (CNPq) for funding and Atlas Assessoria Linguística for language editing.

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How to quote this article

MAGALHÃES. J. B.; STUMM, J. O.; KESSLER, N. C. H.; TURCHETTO, R.; GIOVENARDI, A. R.; BASSO, C. J.; ROS, C. O.; SILVA, R. F. Organomineral fertilizers and soil remineralizer in the initial growth of mycorrhized *Eucalyptus grandis* W. Hill ex Maiden. **Ciência Florestal**, Santa Maria, v. 34, n. 2, e68293, p. 1-19, 2024. DOI 10.5902/1980509868293. Available from: https://doi.org/10.5902/1980509868293. Accessed in: day month abbr. year.