# Effectiveness of arbuscular mycorrhiza and calcite on soil macronutrient content and P uptake in palmarosa (*Cymbopogon martinii*)

Samanhudi[1,2*], *Andriyana* Setyawati [1], *Muji* Rahayu [1], *Djoko* Purnomo [1], and *Aulia Fidia* Syahrina [1]

[1]Department of Agrotechnology, Faculty of Agriculture, Sebelas Maret University, Surakarta 57126, Central Java, Indonesia
[2]Center for Research and Development of Biotechnology and Biodiversity of Sebelas Maret University, Surakarta 57126, Central Java, Indonesia

**Abstract.** Macronutrient levels are critical to support the sustainability and consistency of crop production of palmarosa. This study aims to determine the soil macronutrient content and the phosphorus uptake of palmarosa that cultivated with arbuscular mycorrhiza fungi (AMF) and calcite at various dosages. Experiment through a completely randomized design using AMF and calcite, each with four levels: AMF (0, 5, 15, and 25 g plant$^{-1}$) and calcite (0, 2.5, 5, 7.5 tons ha$^{-1}$). The results showed that the soil condition before AMF and calcite treatment was marginally suitable for palmarosa due to low available P content (7 ppm). The application of calcite increased soil calcium content by 114% directly proportional to the level of soil pH (7.3-7.6) which was positively correlated with the increase in calcite dosages. Dosages of AMF 25 g plant$^{-1}$ and calcite 2.5 tons ha$^{-1}$ suggested to be applied in Tawangmangu, Central Java, to improve soil suitability for palmarosa growing conditions. This application efficiently increases soil macronutrient content, particularly in enhancing the levels of soil $P_2O_5$ by 281%, available P by 57%, and P uptake in palmarosa by 82%.

## 1 Introduction

Palmarosa (*Cympogon martinii*) is an aromatic grass plant with the character of aromatic essential oils such as roses [1]. Palmarosa essential oil has a high value in the cosmetics and fragrance industry [2] and also acts as an antimicrobial and antioxidant in the pharmaceutical industry [3]. Indonesia is one of the top four contributors in meeting the demand for 60 - 70 tons of palmarosa essential oil globally [4]. The environmental carrying capacity for palmarosa cultivation is important to ensure sustainability and consistency of production. Highlands with Andosol-type soils are rich in potential organic matter for palmarosa cultivation [5].

Macronutrient levels in the form of nitrogen (N), phosphorus (P), and potassium (K) are important in palmarosa cultivation because, in one periode harvest, palmarosa can convert N

* Corresponding author: samanhudi@staff.uns.ac.id

(8.24 – 18.00 kg $ha^{-1}$), P (7.37 – 13.46 kg $ha^{-1}$), and K (5.23-12.70 kg $ha^{-1}$) into biomass [6]. Specifically, the biosynthesis of volatile compounds in the form of geraniol, geranyl acetate, linalool, geranial, and β-caryophyllene [7] contained in palmarosa essential oil is highly dependent on the adequacy of P nutrients [8]. Element P is the main substrate for secondary metabolic processes, especially the biosynthesis of the terpenoid pathway [9-10]. The sustainability of palmarosa cultivation requires environmentally friendly and economical inputs to achieve production consistency. Environmentally friendly inputs include arbuscular mycorrhizal fungi (AMF) and calcite using calcite.

Arbuscular mycorrhizal fungi play a role in increasing nutrient uptake in plants even though soil fertility conditions are lacking, and deficient P availability [11]. The AMF inoculation on palmarosa can be an alternative to increase the yield of essential oils and geraniol content [12]. The interaction of AMF with plant roots can increase plant capacity to absorb nutrients and water, drought resistance, as a biological control, and protect plants from exposure to heavy metals [13-14].

Liming using calcite can increase soil fertility and potentially increase essential oils. Alkaline soil can inhibit plant growth and development. Plant response as adaptation in alkaline conditions by increasing antioxidant enzyme activity to reduce excessive oxidative damage [15]. Alkaline stress through 200 g $pot^{-1}$ liming has been proven to raise the content of *superoxide dismutase* (SOD) by 1.02% along with drought stress [16]. The calcite content of 1.157 mg $L^{-1}$ can increase the geraniol content by 89% [17].

The status of soil chemical fertility in palmarosa cultivation land such as in the Tawangmangu highlands is the basis for the development of fertilization technology in palmarosa cultivation because information is still limited. The discussion on AMF and calcite in Andosol is still limited. This study aims to explain the effectiveness of arbuscular mycorrhiza and calcite on macronutrient content and phosphorus uptake in palmarosa cultivation.

# 2 Material and Methods

## 2.1 Time and place of experiment

The experiment lasted from June to November 2023, in Tawangmangu, Central Java, located at 7°39'13" - 7°39'18"S and 111°06' - 111°06' 16" E, specific on 0.3 ha of palmarosa cultivation land with an altitude of 750 meters above sea level. The test site was in a tropical climate, with a daily temperature of 30.3°C and an air humidity of 57.5%, according to the optimum growth and synthesis range of essential oils (temperature 17 - 30°C and humidity 44.5 - 76.5%) [18], the average of maximum light intensity recorded around 54,100 lux following the optimum conditions [19]. The analysis was carried out at the Laboratory of Soil Chemistry and Fertility, Faculty of Agriculture, Sebelas Maret University, Surakarta.

## 2.2 Experiment material and tools

Soil samples for analysis were obtained from 6 points on the cultivated land, while calcite and AMF were applied to palmarosa using a two-factor completely randomized design experiment, AMF dosages (0, 5, 15, and 25 g $plant^{-1}$) and calcite dosages (0, 2.5, 5, and 7.5 tons $ha^{-1}$), So that 16 combinations of treatments were repeated three times each with plant spacing 45 x 45 cm. Planting media, andosol soil mixed with manure fertilizer in a ratio of 4:1, each polybag weighs 15 kg.

Observation parameters include macronutrient levels of soil before and after treatment with parameters measurement method: total N (Kjeldahl), total P and Ca (spectrophotometry), C-Organic (titration), total K (flamephotometry), Available P (Olsen), and P uptake ($H_2SO_4$ wet ashing). Evaluation of macronutrient status based on the weight of the value of each parameter according to the growing conditions of palmarosa (Table 1). The palmarosa P uptake with various dosages of AMF and calcite was analyzed descriptively.

**Table 1.** Palmarosa plant growing requirements [20-21]

| Criteria | Land Suitability Classes | | | |
|---|---|---|---|---|
| | S1 | S2 | S3 | **N** |
| Temperature (T) | | | | |
| Daily average temperature (°C) | 22-25 | 16-22 | - | > 36 |
| | | 25-36 | | < 16 |
| Water availability (wa) | | | | |
| Humidity (%) | 60-80 | - | - | < 50 |
| | | | | > 100 |
| Nutrient retention (nr) | | | | |
| CEC (cmol+/kg) | > 16 | ≤ 16 | - | - |
| BS (%) | > 50 | 35-50 | < 35 | - |
| Actual soil pH ($H_2O$) | 5.5-6.5 | 4.5-5.5 | < 4.5 | - |
| | | 6.5-8.5 | > 8.5 | - |
| Organic-C (%) | > 1.2 | ≤ 1.2 | - | - |
| Nutrient availability (na) | | | | |
| Total-N (%) | 0.21-0.50 | 0.10-0.20 | < 0.10 | - |
| $P_2O_5$ (mg/100 g) | 21-40 | 15-20 | < 15 | - |
| $K_2O$ (mg/100 g) | < 10 | 10-20 | 21-40 | - |

Remarks: CEC (Cation Exchangeable Capacity), BS (Base Saturation), S1: Highly suitable, S2: Moderately suitable, S3: Marginally suitable, N: Currently unsuitable

# 3 Result

## 3.1 Soil Macronutrient Content

### *3.1.1 Initial soil analysis (before AMF and $CaCO_3$ treatment)*

The soil as a medium for planting palmarosa is andosol which comes from the volcanic area of Tawangmangu, Central Java, with a blackish-brown character and rich in organic matter. Initial soil analysis before calcite application showed content: total N and K very high, $P_2O_5$ and C-organic moderate, Available P, exchangeable Al, and CEC very low, pH neutral, field capacity 63.18%, clay textured. Based on these results, soil fertility can be stated in the medium category (Table 2).

**Table 2.** Results of soil analysis before AMF and calcite treatment

| Parameter | Unit | Result | Category |
|---|---|---|---|
| Total N | % | 1.09 | Very high |
| $P_2O_5$ | mg 100 $g^{-1}$ | 14.66 | Moderate |
| Available P | Ppm | 7 | Low |
| Total K | me 100 $g^{-1}$ | 73.8 | Very high |
| C-Organic | % | 2.26 | Moderate |
| CEC | cmol (+) $kg^{-1}$ | 2.31 | Very low |
| Actual soil pH ($H_2O$) | - | 6.7 | Neutral |
| Field capacity | % | 63.18 | - |
| Exchangeable Al | me 100 $g^{-1}$ | 0.2 | - |

### *3.1.2 Final soil analysis (after AMF and $CaCO_3$ treatment)*

Application of calcite with dosages 0, 2.5, 5, and 7.5 tons $ha^{-1}$ increases soil pH according to successive dosage increases of 6.7, 7.3, 7.4, and 7.6 (Table 3). This is related to an increase in soil Ca content of 6.7, 14.4, 14.5, and 19.1 me 100 $g^{-1}$, with a very high correlation coefficient ($r$ = 0.99). The application of calcite increases actual soil pH, available P, $Ca^{2+}$, and degrades exchangeable Al in the soil. Application of calcite very soluble in water, it will release $OH^-$ ions to increase the saturation of alkaline ions, but it is limited according to the percentage *of soil buffer* (humus) [22].

**Table 3.** Results of soil analysis after AMF and calcite treatment at various dosages

| Calcite dosages (ton $ha^{-1}$) | Total N (%) | $P_2O_5$ | Total K | Ca | Available P (ppm) | C-Organic (%) | pH |
|---|---|---|---|---|---|---|---|
| | | (mg 100 $g^{-1}$) | | | | | |
| 0 | 0.62 | 70 | 43.2 | 6.7 | 14 | 3.6 | 6.7 |
| 2.5 | 0.55 | 56 | 26.0 | 14.4 | 11 | 12.2 | 7.3 |
| 5 | 0.25 | 73 | 31.4 | 14.5 | 15 | 7.5 | 7.4 |
| 7.5 | 0.51 | 51 | 35.0 | 19.1 | 10 | 6.8 | 7.6 |

### 3.2 Palmarosa P Uptake

Application of calcite at 2.5 tons $ha^{-1}$ increased palmarosa P uptake by 17.5% compared to control. The level of P uptake in palmarosa with calcite dosages of 5 and 7.5 tons $ha^{-1}$ less than 2.5 tons $ha^{-1}$ calcite treatment. Palmarosa with AMF innoculation has the level of P uptake higher than without AMF, the treatment of AMF 15 g $plant^{-1}$ with calcite 7.5 tons $ha^{-1}$ increasing P uptake by 75%. Application of AMF 5 g $plant^{-1}$ without calcite and application of calcite 2.5 tons $ha^{-1}$ with AMF 25 g $plant^{-1}$ increase up to 71,4% and 68,4% respectively (Table 4).

**Table 4.** P uptake in palmarosa (kg $ha^{-1}$) at various dosages of AMF and calcite

| Calcite dosages (ton $ha^{-1}$) | AMF dosages (g $plant^{-1}$) | | | | |
|---|---|---|---|---|---|
| | 0 | 5 | 15 | 25 | Average |
| 0 | 13.13 | 23.15 | 16.25 | 14.91 | 16.86 |
| 2.5 | 17.28 | 19.67 | 17.08 | 23.92 | 19.49 |
| 5 | 16.35 | 15.60 | 12.35 | 21.23 | 16.38 |
| 7.5 | 16.11 | 17.13 | 23.39 | 13.70 | 17.58 |
| **Average** | 15.72 | 18.88 | 17.26 | 18.44 | |

## 4 Discussion

### 4.1 Soil Macronutrient Content

#### *4.1.1 Initial soil analysis (before AMF and $CaCO_3$ treatment)*

Andosol as a clay texture experimental medium has a small soil pore size [23] So that the consistency depends on the moisture content, the moisture content is higher than the capacity of the field, then the soil will have an adhesive and plastic consistency [24]. This is due to the high levels of clay, humus, and moderate C-Organic [25]. Soil fertility based on Andosol macronutrient content at the palmarosa cultivation site is categorized as medium, the levels of N, K, and C-Organic are relatively high, but the total P content and the availability of P element for plants are low (14.6 mg 100 $g^{-1}$ and 7 ppm) For the cultivation of palmarosa (15 - 40 mg 100 $g^{-1}$).

The availability of P is high in soils with a neutral pH (6.0-7.0), but the availability of P is also affected by soil type. Soils with a high percentage of klei can absorb P in high soils as well [26]. Soil conditions in palmarosa cultivation land with high levels of N, K, and C-Organic (S1), while total P is moderate and the availability P is low level (S3) need to be improved to meet the requirements for growing palmarosa (Table 1). Macronutrient are needed in large enough quantities, generally given in the form of compounds [27] that is important for plant growth and development [28].

#### *4.1.2 Final soil analysis (after AMF and $CaCO_3$ treatment)*

Although the application of calcite in the planting medium at various dosages did not show much difference, it can be stated that the dosages of calcite 2.5 and 5 tons $ha^{-1}$ meet the requirements for growing palmarosa (Table 1). The levels of total N and C-organic in the category are highly suitable (S1), the levels of $P_2O_5$, available P, and the soil pH are moderately suitable (S2), as well as the total K levels are marginally suitable (S3). Application of calcite in various dosages did not affect total N (0.25-0.62%), available P (10-15 ppm), total K (26-43 me 100 $g^{-1}$), and C-Organic (3.6-12.6%). A decrease in nutrient levels in the soil can occur because it is absorbed by plants and may also be lost due to washing or oxidation.

The application of calcite does not significantly increase the total N soil. Element N has a very *mobile* property of undergoing leaching, so can decrease drastically, all forms of N in the soil will be converted into biomass or oxidized to $NO_3$ [29]. The nutrient status of N, P, and K due to the application of the same basic fertilizer increases macronutrient levels that are not much different. Manure as a basic fertilizer in palmarosa cultivation contains organic matter that can improve soil fertility and health [30]. Organic basic fertilizers become a provider of macro and micronutrients [31-32] especially N supply that present a role in plant primary metabolism associated with photosynthesis [33-36].

Calcite is a type of lime that could enhance the value of pH and organic materials of soil [37-38]; beside that calcite has low ability to increase available P content, in *calcareous soils* P-available is low [39]. The 7.5 tons $ha^{-1}$ calcite dosage had lower available P levels than the 0, 2.5, and 5 tons $ha^{-1}$ dosages. This is because of the binding of P by Ca in the soil, the pH that is getting higher due to the high lime content will also result in the availability of P decreasing by the fixation of Ca contained in calcite so that it will form $Ca(PO_4)_2$ [40].

The application of calcite increases the content of C-organic, which generally comes from the application of organic matter into the soil undergoes further degradation and is soon converted into $CO_2$ [41]. The application of calcite causes the soil atmosphere to become oxidative so that there is a release of $CO_2$ causing the carbon content in the soil to be high but immediately drop and evaporate through the soil pores, application 7.5 tons $ha^{-1}$ calcite indicated that pH 7.5 to 7.6 resulted in low $P_2O_5$, available P, and C-organic [42].

### 4.2 Palmarosa P Uptake

The uptake of P in palmarosa at various dosages of calcite did not increase significantly. Calcite application also not significant in increasing the P and N uptake of maize [43]. That is in line with plants cannot meet the needs of N if there is insuficient P [44]. The efficiency of phosphate uptake in available forms is less than optimal in alkaline soils. The phosphorus efficiency is not more than 30% due to fixation in the form of $Ca(PO_4)_2$ in alkaline and calcareous soils [15]. In the other hand, application of AMF on palmarosa showed higher P uptake compared to the treatment without AMF. The increase in P uptake with AMF 5 g plant$^{-1}$ at various dosages of calcite reached 20%. Planting media with a calcite 2.5 tons ha$^{-1}$, which is the ideal dosages for enhance the macronutrient content of palmarosa cultivation land, along with the application of AMF 25 g plant$^{-1}$ effectively increased P uptake by 82% than control and give the highest P uptake about 38% compared to the treatment of calcite 2.5 tons ha$^{-1}$ without AMF also 21.6% and 40% higher than calcite 2.5 tons ha$^{-1}$ with AMF 5 and 15 g plant$^{-1}$ respectively.

The efficiency of phosphorus uptake in plants that are symbiotic with AMF allows AMF hyphae to expand root tissue, AMF can secrete compounds that help dissolve unavailable P into available to plants [45]. The availability of plant nutrients is highly dependent on the condition of the rhizosphere such as soil are moisture, temperature and soil aeration [46]. Sufficient amount of the nutrient content could enhance the volume of plant roots for better nutrient uptake ability [47].

The use of AMF in palnting media without calcite shows that the dosage of AMF 5 g plant$^{-1}$ already can increase the P uptake but AMF at dosages 15 and 25 g plant$^{-1}$ shows lower result. This also occurs on panting media with calcite 7.5 tons ha$^{-1}$ which P uptake optimum with application of AMF 15 g plant$^{-1}$. Based on this study, the dosage of AMF directly proportional to the infectivity of AMF in palmarosa roots ($r$ = 0,806). The excessive dosages of AMF can result in nutrient imbalances, beside the high content of Ca due to calcite application could form Ca-P binding, the interaction of soil microbes with plant roots also affects the availability of macronutrients in the rhizosphere [48].

### 4.3 Recommendation For Land Management

The application of AMF and calcite improved soil macronutrient content and P uptake in palmarosa. Soil suitability are needed to support the growth of plants [49]. The application of AMF in soil conditions with high organic matter, total N, and K levels, moderate $P_2O_5$, and low on P availability can optimize plant P uptake [50]. Improving the macronutrient content using calcite can increase pH and soil porosity, good porosity of soil could improving soil structure and ability in maintaining groundwater, and enhanced nutrient absorption. Based on this result, AMF and calcite are recommended to be applied in Tawangmangu in palmarosa cultivation.

## 5 Conclusion

Soil condition before AMF and calcite treatment has $P_2O_5$ levels and P availability that marginally suitable for palmarosa cultivation. The application of calcite positively correlated with Ca and soil pH levels. The 2.5 tons ha$^{-1}$ calcite efficiently increased soil macronutrient content at available P by 57% and $P_2O_5$ levels by 114% that suitable for palmarosa cultivation. Combination of AMF 25 g plant$^{-1}$ with calcite 2.5 tons ha$^{-1}$ successfully increased palmarosa P uptake about 82%, therefore this treatment is suggested for palmarosa cultivation in Tawangmangu, Central Java.

The authors sincerely thank the Directorate of Research, Technology, and Community Services (DRTPM) under the Ministry of Education, Culture, Research, and Technology Republic of Indonesia for offering financial support for this research through the Fundamental Research scheme in the fiscal year 2023.

## References

1. R. Smitha and P. Manivel, Genetic improvement of palmarosa (Cymbopogon martinii var. motia) for herbage and essential oil yield through polycross method of breeding. Electronic

Journal of Plant Breeding. **12**, 1 (2021).
2. G. R. Smitha and V. S. Rana, Variations in essential oil yield, geraniol and geranyl acetate contents in palmarosa (Cymbopogon martinii, Roxb. Wats. var. motia) influenced by inflorescence development. Industrial Crops and Products. **66**, (2015).
3. B. Jummes, W. G. Sganzerla, C. G. da Rosa, C. M. Noronha, M. R. Nunes, F. C. Bertoldi, and P. L. M. Barreto, Antioxidant and antimicrobial poly-ε-caprolactone nanoparticles loaded with Cymbopogon martinii essential oil. Biocatalysis and Agricultural Biotechnology. **23**, January (2020).
4. S. Latha, S. Kameshwari, T. S. Kj, C. Sree, L. K. Research, V. Tn, and T. Saraswathi, Morphological and cytogenetic studies in wild species of Cymbopogon martinii (Roxb.) Wats from Kodaicanal (T.N.). ~ 175 ~ Journal of Medicinal Plants Studies. **5**, 2 (2017).
5. E. Suryani and H. Idris, Produktivitas Tanaman Palmarosa ( Cymbopogon martinii ) pada Tanah Ultisol dengan Pemberian Beberapa Pupuk Organik. Jurnal Galung Tropika. **10**, 2 (2021).
6. M. Jayalakshmi, S. G. Wankhade, and P. M. Rao, Performance of different levels of Nitrogen and Phosphorus on herbage yield, nutrient content and uptake of rain fed Palmarosa (Cymbopogan martini var. Motia)- A review. Agricultural Reviews. **34**, 4 (2013).
7. A. K. Kesharwani, R. P. Singh, A. Kulshreshtha, and A. Khrisna, ESSENTIAL OILS COMPOSITION OF CYMBOPOGON MARTINII GROWN IN SEMI-ARID REGION OF UTTAR PRADESH , INDIA. Scientist. **3**, 3 (2023).
8. A. Akbar, A. Boceng, and A. Robbo, EVALUASI KESESUAIAN LAHAN UNTUK PENGEMBANGAN TANAMAN JAGUNG (Zea mays L.) DI KECAMATAN HERLANG, KABUPATEN BULUKUMBA. AGrotekMAS Jurnal Indonesia: Jurnal Ilmu Peranian. **1**, 3 (2021).
9. M. Nazir, M. Saleem, M. I. Tousif, M. A. Anwar, F. Surup, I. Ali, D. Wang, N. Z. Mamadalieva, E. Alshammari, M. L. Ashour, A. M. Ashour, I. Ahmed, Elizbit, I. R. Green, and H. Hussain, Meroterpenoids: A comprehensive update insight on structural diversity and biology. Biomolecules. **11**, 7 (2021).
10. A. Murthy, S. Latha, and K. Murthy, Studies on the Differential Gene Expression of Terpenoid Biosynthesis Pathway from Wild Cymbopogon martinii ( Roxb .) Studies on the Differential Gene Expression of Terpenoid Biosynthesis Pathway from Wild Cymbopogon martinii ( Roxb .). Indian Journal of Natural Sciences. **12**, 70 (2022).
11. M. A. Salim, Effect of Glomus manihotis inoculation and salt stress on antioxidant and biochemical properties of Chia (Salvia hispanica L.). Sains Tanah. **20**, 2 (2023).
12. U. Pankaj, R. S. Verma, A. Yadav, and R. K. Verma, Effect of arbuscular mycorrhizae species on essential oil yield and chemical composition of palmarosa (Cymbopogon martinii) varieties grown under salinity stress soil. Journal of Essential Oil Research. **31**, 2 (2019).
13. H. Sahputra, S. Suswati, and G. Gusmeizal, Efektivitas aplikasi kompos kulit kopi dan Fungi mikoriza arbuskular terhadap produktivitas jagung manis. Jurnal Ilmiah Pertanian ( JIPERTA). **1**, 2 (2019).
14. V. R. Cahyani, D. W. Kinasih, Purwanto, and J. Syamsiyah, Spore reproduction, glomalin content, and maize growth on mycorrhizal pot culture using acid mineral soil-based media. Sains Tanah. **19**, 1 (2022).
15. D. Liu, Y. Ma, M. Rui, X. Lv, R. Chen, X. Chen, and Y. Wang, Is High pH the Key Factor of Alkali Stress on Plant Growth and Physiology? A Case Study with Wheat (Triticum aestivum L.) Seedlings. Agronomy. **12**, 8 (2022).
16. A. D. R. Riyadi and D. U. Siswanti, Effect of Alkaline and Drought Stress on Growth and SOD (Superoxide dismutase) Content in Basil Plant (Ocimum americanum L.). Jurnal Biodjati. **7**, 1 (2022).
17. V. D. Zheljazkov, T. Astatkie, U. Norton, and E. A. Jeliazkova, Gypsum and coal-bed methane water modify growth media properties, nutrient uptake, and essential oil profile of lemongrass and Palmarosa. Agronomy. **9**, 6 (2019).
18. P. S. Kakaraparthi, K. V. N. S. Srinivas, J. K. Kumar, A. N. Kumar, D. K. Rajput, and S. Anubala, Changes in the essential oil content and composition of palmarosa (Cymbopogon martini) harvested at different stages and short intervals in two different seasons. Industrial Crops and Products. **69**, (2015).
19. Nugraha, Aviasti, A. Nasution, A. Reni, D. S. Mulyati, and C. Nursagita, Pemanfaatan Minyak

Atsiri Jenis Sereh Wangi: Budidaya, Penyulingan dan Pengembangan Teknologi. UNISBA Press. (2019).
20. Eviati;, Sulaeman;, L. Herawaty, L. Anggria, Usman, H. E. Tantika, R. Prihatini, and P. Wuningrum, *Analisis Kimia Tanah, Tanaman, Air, Dan Pupuk*, (2023).
21. Wahyunto, Hikmatullah, E. Suryani, C. Tafakresnanto, S. Ritung, A. Mulyani, Sukarman, K. Nugroho, Y. Sulaeman, Y. Apriyana, S. Suciantini, A. Pramudia, Suparto, R. E. Subandiono, T. Sutriadi, and D. Nursyamsi, *Pedoman Penilaian Kesesuaian Lahan Untuk Komoditas Pertanian Strategis Tingkat Semi Detail Skala 1:50.000*, (2016).
22. N. R. Wandansari, Soemarno, R. Suntari, and S. Kurniawan, The role of humic acid from various composts in improving degraded soil fertility and maize yield. Journal of Degraded and Mining Lands Management. **10**, 2 (2023).
23. T. Woignier, L. Rangon, F. Clostre, C. Mottes, P. Cattan, J. Primera, and M. Jannoyer, Physical limitation of pesticides (chlordecone) decontamination in volcanic soils: fractal approach and numerical simulation. Environmental Science and Pollution Research. **27**, 33 (2020).
24. M. Anda and R. A. Dahlgren, Mineralogical and surface charge characteristics of Andosols experiencing long-term, land-use change in West Java, Indonesia. Soil Science and Plant Nutrition. **66**, 5 (2020).
25. S. R. Utami, F. Mees, M. Dumon, N. P. Qafoku, and E. Van Ranst, Charge fingerprint in relation to mineralogical composition of Quaternary volcanic ash along a climatic gradient on Java Island, Indonesia. CATENA. **172**, (2019).
26. Y. Zhang, S. Huang, D. Guo, S. Zhang, X. Song, K. Yue, K. Zhang, and D. Bao, Phosphorus adsorption and desorption characteristics of different textural fluvo-aquic soils under long-term fertilization. Journal of Soils and Sediments. **19**, 3 (2019).
27. H. Prabowo, Samanhudi, E. Yuniastuti, and A. Yunus, Effects of media combination with concentration of ab-mix nutrient on growth of banana shoots on in vitro. Bulgarian Journal of Agricultural Science. **24**, 3 (2018).
28. S. Mardhikasari, A. Yunus, and S. Samanhudi, Modification of Media for Banana In Vitro Propagation with Foliar Fertilizer and Coconut Water in cv. Rajabulu. Caraka Tani: Journal of Sustainable Agriculture. **35**, 1 (2019).
29. F. Sapalina, E. N. Ginting, and F. Hidayat, Bakteri penambat nitrogen sebagai agen biofertilizer. Warta Pusat Penelitian Kelapa Sawit. **27**, 1 (2022).
30. Samanhudi, A. Yunus, B. Pujiasmanto, V. R. Cahyani, and D. S. Lestariana, The effect of arbuscular mycorrhiza and organic manure on soybean growth and nutrient content in indonesia. Bulgarian Journal of Agricultural Science. **23**, 4 (2017).
31. S. Samanhudi, A. Yunus, and B. Pujiasmanto, Turmeric organic cultivation in the biopharmaca Cluster, Karanganyar regency. Caraka Tani: Journal of Sustainable Agriculture. **33**, 1 (2018).
32. Samanhudi, B. Pujiasmanto, Sudadi, I. H. Putra, and H. M. Mumtazah, The fficiency of Mycorrhiza biofertilizer treatment to the growth and yield of soybean. IOP Conference Series: Earth and Environmental Science. **142**, 1 (2018).
33. R. Y. A. Dawiyah, A. Yunus, Samanhudi, Y. Widiyastuti, and Widodo, Shading and vermicompost effect on growth and flavonoid content of Tapak Liman (Elephantopus scaber L.). IOP Conference Series: Earth and Environmental Science. **142**, 1 (2018).
34. A. Yunus, Samanhudi, N. Brahmanto, and Y. Widyastuti, Artemisia annua respon to various types of organic fertilizer and dose in lowland. IOP Conference Series: Earth and Environmental Science. **142**, 1 (2018).
35. M. N. A. Muktiyanta, Samanhudi, A. Yunus, B. Pujiasmanto, and S. Minardi, Effectiveness of cow manure and mycorrhiza on the growth of soybean. IOP Conference Series: Earth and Environmental Science. **142**, 1 (2018).
36. Samanhudi, Sudadi, A. Yunus, B. Pujiasmanto, and W. Mahasti, Pengaruh Kascing dan Mikoriza terhadap Pertumbuhan dan Hasil Tribulus terrestris. Jurnal Agrotek Indonesia. **2**, 1 (2017).
37. D. Sacristán, A. González–Guzmán, V. Barrón, J. Torrent, and M. C. Del Campillo, Phosphorus-induced zinc deficiency in wheat pot-grown on noncalcareous and calcareous soils of different properties. Archives of Agronomy and Soil Science. **65**, 2 (2019).
38. K. Matsui, Y. Takata, S. Matsuura, and R. Wagai, Soil organic carbon was more strongly linked with soil phosphate fixing capacity than with clay content across 20,000 agricultural soils in Japan: a potential role of reactive aluminum revealed by soil database approach. Soil

Science and Plant Nutrition. **67**, 3 (2021).
39. P. Mehra, B. Sarkar, N. Bolan, S. Chowdhury, and J. Desbiolles, Impact of carbonates on the mineralisation of surface soil organic carbon in response to shift in tillage practice. Geoderma. **339**, (2019).
40. A. Guo, L. Ding, Z. Tang, Z. Zhao, and G. Duan, Microbial response to CaCO 3 application in an acid soil in southern China. Journal of Environmental Sciences (China). **79**, (2019).
41. M. R. B. Prasetyo and B. Hermiyanto, Pengaruh Pemberian Jamur Mikoriza Arbuskular dan Batuan Fosfat terhadap Infeksi Akar, Kadar P, Pertumbuhan dan Produksi Tanaman Sorgum (Sorghum bicolor L. Moench). Berkala Ilmiah Pertanian. **5**, 4 (2022).
42. A. Khalisha, R. Widyastuti, and I. A. Chaniago, Use of phosphorus- and potassium-solubilizing multifunctional microbes to support maize growth and yield. Sains Tanah. **19**, 1 (2022).
43. P. Rawat, S. Das, D. Shankhdhar, and S. C. Shankhdhar, Phosphate-Solubilizing Microorganisms: Mechanism and Their Role in Phosphate Solubilization and Uptake. Journal of Soil Science and Plant Nutrition. **21**, 1 (2021).
44. W. P. Dinda, E. Triharyanto, and Samanhudi, Effects of mulch on growth and yield of garlic bulbils at various fertilizing doses. IOP Conference Series: Earth and Environmental Science. **423**, 1 (2020).
45. L. Prasetyo, Y. Widyastuti, A. Yunus, and Samanhudi, The growth response of Artemisia annua L. to organic fertilizer type in lowland. IOP Conference Series: Earth and Environmental Science. **142**, 1 (2018).
46. N. Begum, C. Qin, M. A. Ahanger, S. Raza, M. I. Khan, M. Ashraf, N. Ahmed, and L. Zhang, Role of Arbuscular Mycorrhizal Fungi in Plant Growth Regulation: Implications in Abiotic Stress Tolerance. Frontiers in Plant Science. **10**, September (2019).
47. M. Rahayu, E. Purwanto, A. Setyawati, A. T. Sakya, Samanhudi, A. Yunus, D. Purnomo, G. C. Handoyo, R. B. Arniputri, and S. Na'Imah, Growth and yield response of local soybean in the giving of various organic fertilizer. IOP Conference Series: Earth and Environmental Science. **905**, 1 (2021).
48. M. Sheikh-Assadi, A. Khandan-Mirkohi, M. R. Taheri, M. Babalar, H. Sheikhi, and S. Nicola, Arbuscular Mycorrhizae Contribute to Growth, Nutrient Uptake, and Ornamental Characteristics of Statice (Limonium sinuatum [L.] Mill.) Subject to Appropriate Inoculum and Optimal Phosphorus. Horticulturae. **9**, 5 (2023).
49. Pambudi Aji Nugroho, Yuli Widyastuti, Samanhudi, and Ahmad Yunus, Growth Response of Artemisia annua by Effect of Types and Composition of Organic Fertilizer in Lowland. Journal of Agricultural Science and Technology B. **7**, 5 (2017).
50. T. R. Ferreira, L. F. Pires, D. Wildenschild, R. J. Heck, and A. C. D. Antonino, X-ray microtomography analysis of lime application effects on soil porous system. Geoderma. **324**, (2018).