Eurasian Journal of Soil Science 2024, 13(1), 59 - 69

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org

Improving microbial properties in Psamments with mycorrhizal fungi, amendments, and fertilizer

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Article Info

Received : 15.07.2023

Accepted : 23.11.2023

Available online : 27.11.2023

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Abstract

Psamments is sandy soil with a texture class of fine loamy sand or coarser in all layers, deposited sands such as dunes in beach lands with low soil biological fertility. Adding mycorrhizal, soil amendments, and inorganic fertilizers could improve soil fertility. This research aimed to investigate the effect of mycorrhizal, soil amendments, and inorganic fertilizers on soil organic carbon (SOC), microbial biomass carbon (MBC), glomalin-related soil protein (GRSP), and root infections in Psamments. This research was a pot experimental in screenhouse, arranged in a factorial completely randomized design with three factors: three of mycorrhizal doses, M0 = 0 spore pot^{-1}, M1 = 3 spores pot^{-1} and M2 = 6 spores pot^{-1}; three types of soil amendments, P0 = non amendment, P1 = cow dung 60 t ha^{-1}, P2 = rice husk biochar (RHB) 25 t ha^{-1}; and two doses of inorganic fertilizer, A0 = 0 kg ha^{-1}, A1 = 100 kg ha^{-1} NPK (15:15:15) fertilizer, replied three times. The results showed that mycorrhizal combination with RHB and inorganic fertilizer increased MBC up to 23 times than control. The combination of mycorrhizal-cow dung-inorganic fertilizer was the highest of total-GRSP (4.4 times) and mycorrhizal dose 6 spores pot^{-1} with both amendments and inorganic fertilizer increase root infection up to 90%. It was proven that mycorrhizal with soil amendments and inorganic fertilizers could improve the microbial properties of Psamments.

Keywords: Cow dung, low fertility, rice husk biochar, soil organic, total GRSP.

Introduction

The nature that finite of land availability causes the emergence of a tight full competition for land use. This usually occurs between the agricultural and non-agricultural sectors, those resulting in actions to convert the function of agricultural land (Agricultural Land Conversion) (Sitko and Jayne, 2014). The agricultural land conversion to non-agricultural functions has increased yearly due to the high human need for shelter (Rondhi et al., 2018). Somehow, the need for food has also increased, in line with the increasing population in Indonesia (Safitri and Sihaloho, 2020). Azadi et al. (2011) also stated that the most common problem in developing countries is a massive population and high food consumption. The better solution to this problem is agricultural extensification by managing sub-optimal soil such as sandy soil or Psamments (Handika et al., 2016).

Countries worldwide know that Indonesia is a very large archipelagic country with a total of 17,480 islands (Torry and Kusumo, 2010) spread from Sabang to Merauke. The ocean bounds each island, and the border between the edge of the island and the ocean is called the coastline (Alfahmi et al., 2019). Indonesia's coastline is composed of loosely structured soil, the particles are not bound together, and there are no clay particles, called sandy soil or Psamments (Vezzani et al., 2018). Psamments in Indonesia, approximately about 1,060,000 ha and potential to cultivate (Kelland et al., 2020). Nevertheless, there are several obstacles in the use of lands such as arid environmental conditions (Meftah et al., 2019), low numbers of microorganisms

: https://doi.org/10.18393/ejss.1396572

: http://ejss.fesss.org/10.18393/ejss.1396572

Publisher : Federation of Eurasian Soil Science Societies

e-ISSN : 2147-4249

(Pakbaz et al., 2018), and low of biological activities (Wong et al., 2020), so the decomposition process is not going well and humification is not running optimally (Goebel et al., 2011), and not soil aggregation is created. As a result, organic material is not well decomposed and low in content, so the soil fertility is not optimal and less supportive of plant growth. The low biological activity of Psamments is caused by physical problems of the soil and climate, especially microclimate which are less friendly and become a barrier to plants suitable for growth.

Solving the problem of Psamments using mycorrhizal, especially endomycorrhizal according to Bai et al. (2002) was effective because mycorrhizal plays an active role in critical conditions by increasing nutrient uptake of phosphorus (Clausing and Polle, 2020) and other essential microelements (Zn, Co, and Mo), increasing soil aggregation so that soil microbial activity that is beneficial to plants also increases and protects plants from root pathogens (Cheng et al., 2022). Samuel and Veeramani (2021) also stated by their research by comparing the growth of plants with mycorrhizal colonization and none in the same soil conditions. The result showed that plants with mycorrhizal colonization absorb nutrients more significantly than non-mycorrhizal colonization. The problem of Psamments can also be overcome by providing a soil amendment to improve the characteristics of biology, chemistry, and soil physics. The biological characteristics of soils were markedly enhanced by the application of solid biofertilizers and organic amendments, particularly SOC (Fitriatin et al., 2021). Sukartono et al. (2022) reported that biochar-based organic amendments significantly enhanced soil organic carbon and cation exchange capacity in the sandy loam soils. The long-term carbon absorption and glyphosate-biochar interaction during adsorption can be enhanced by rice husk biochar. Enhancing the cation exchange capacity, electrical conductivity, pH H_2O, and soil organic matter, Inceptisols ameliorated with rice husk biochar raised the soil surface charge (ΔpH) (Herviyanti et al., 2022) and increased fertilizer absorption by root (Nurmalasari et al., 2021).

Prasad and Kothari (2022), the application of cow dung to soil had some advantages to yield, cation exchange capacity (CEC), soil organic matter percentage, pH, and direct impact on food security and human health. The low fertility of Psamments can be improved by applying inorganic fertilizer (Sharma et al., 2020) because it will provide a sufficient supply of nutrients for plant growth. Various studies that have been conducted have yielded less than optimal results. Hapsoh et al. (2017) state that the application of inorganic fertilizers resulted in the lowest growth because the nutrients supplied by inorganic fertilizers are leached due to sandy soil having loose consistency (Fang et al., 2021). Likewise, a single application of rice husk biochar has no significant effect on SOC. Adding mycorrhizal alone does not significantly affect nutrient absorption (Sun et al., 2022).

The novelty of this research is three treatment combinations of mycorrhizal, soil amendments, and inorganic fertilizer to improve microbial characteristics in Psamments. Thus, the aimed of the research was to investigate the effect of three treatment combinations on soil organic carbon (SOC), microbial biomass carbon (MBC), glomalin-related soil protein (GRSP), and root infections in Psamments through a pot experiment.

Material and Methods

This research was conducted for 6 months at the green house experimental garden Faculty of Agriculture, Universitas Sebelas Maret located in Jumantono, Karanganyar, Indonesia. A pot experiment arranged with a factorial Completely Randomized Design consisting of three treatment factors: mycorrhizal, types of soil amendments, and doses of inorganic fertilizers. The mychorrhizal fungus used in the experiment is endomycorrhizal, consist of *Glomus manihotis*, *Glomus intraradices*, *Glomus aggrega*tum, *Acaulospora* sp., *Gigaspora* sp., that total spore density is 33.2% spore/50grams. The characteristics of cow dung: pH H_2O (1:5) 7.88; total organic carbon (TOC) 16.62% (dry combustion) (Soil Survey Staff, 2022); total Nitrogen 0.64% (Kjeldahl) (FAO, 2021), and C/N Ratio 26.39. The characteristics of rice husk biochar: water content 8.11%, pH H_2O (1:5) 6.14; total organic carbon (TOC) 18.07%; total Nitrogen 0.54% (Kjeldahl), and C/N Ratio 33.3. Mycorrhizal dose consists of three levels, namely 0 spore/pot (M0), 3 spores/pot (M1), 6 spores/pot (M2), three types of soil amendments: non amendment (P0), cow dung 60 t ha^{-1} (P1), rice husk biochar (RHB) 25 t ha^{-1} (P2), and two levels of inorganic fertilizers, 0 kg ha^{-1} (A0) and 100 kg ha^{-1} (A1) NPK fertilizer (15:15:15). There were 18 treatment combinations with 3 replications so there were 54 experimental units.

The soil used was Psamments from Bantul Regency, Yogyakarta Province, Indonesia. The initial soil analysis of Psamments according to Page et al. (1982), the result showed that pH H_2O (1:2.5) 7.12; soil organic carbon 0.18%; cation exchange capacity 4.43 cmol kg^{-1}; total N 0.015%; available P_2O_5 7.34 mg kg^{-1}, available K 0.27 cmol kg^{-1}; and soil texture was sand (sand 92.23%; silt 6.81%; and clay 0.96%). According to soil fertility category by Husein et al. (2021), the parameters of pH H_2O is neutral, SOC, CEC, total nitrogen, available P_2O_5, and available K are very poor. Based on the initial soil analysis, it can be concluded that the Psamments had low fertility. There are many steps of this research. First, sieving soil with a 2 mm sieve to separate the soil fraction from the rock. Next, a quantity of soil weighing 10 kg was carefully measured and thereafter placed within a polybag. Subsequently, the soil was combined with the appropriate soil amendments based on the designated treatment and subjected to a four-week incubation period. After 4 weeks of incubation, planting red chili (*Capsicum annuum* L.) seedlings is carried out together with the mycorrhizal application according to the treatment. Inorganic fertilizers were applied a week after planting.

Watering is done by adding the water until field capacity and weeding every 2 days until 110 days after planting. At 110 days, the soil and root sample was collected. Soil samples were analyzed including SOC (Walkey and Black) (Black et al., 2016), microbial biomass carbon (fumigation and extraction), soil sample extracted with 0.5 M K_2SO_4, shaked for 30 minutes and filtered with Whatman 42, and then fumigated, last measured the absorbance using a spectrophotometer at 561 nm (Vance et al., 1987), easily extracted glomalin (EE-GRSP) by autoclaving soil samples with sodium citrate 20 Mm pH 7 for 30 minutes, total-GRSP by autoclaving of soil samples with 50 Mm sodium citrate pH 8 for one hour (Wright and Upadhyaya, 1998). Analysis of root samples includes calculating root infection (Phillips and Hayman, 1970). The data were subjected to statistical analysis using a one-way analysis of variance (ANOVA) test with a significance level of 5% and DMRT test level of 5% with the Minitab version 16. To determine the relationship between variables using the Pearson correlation test.

Results and Discussion

Effects of mycorrhizal, soil amendments and inorganic fertilizers on Psamments characteristics

Soil organic carbon (SOC)

The application of cow dung significantly affected to increase SOC, levels up to 2.36 times compared to non-amendment (Figure 1). Biochar rice husk application increased SOC value 1.71 times than non-amendment, the lowest is in non-amendment (0.14%). Ebido et al. (2021) reported that the adding of rice husk biochar increased soil organic carbon generally, with the greatest increments (37%) in maximum rate. Organic amendment have been found to contribute more to soil organic carbon (SOC) than inorganic fertilizers (Supriyadi et al., 2018). Saleem et al. (2022) stated that biochar applied to sandy loam soil can increase humic acid, fulfill acid, and impact the soil's total SOC. Baiamonte et al. (2021) also stated that biochar was used as a recommendation for the restoration of degraded and marginal lands through increased SOC and nutrients to increase crop productivity. He et al. (2020) reported that mycorrhizal application contributes to the SOC presence. The mechanism is mycorrhizal symbiosis association shaped extraradical hyphae and its hyphal turnover to the soil and added SOC in the form of glomalin (Paterson et al., 2016; Syamsiyah et al., 2018). This statement was assured by the positive correlation (r=0.467**) between SOC and glomalin. Meanwhile, mycorrhizal hyphae have the ability to accelerate litter's decomposition to aid the accumulation of SOC presence and increase plant capability to uptake Nitrogen (Hodge and Fitter, 2010). Mycorrhizal also has a function to promote SOC's retention into aggregates (Wei et al., 2019).

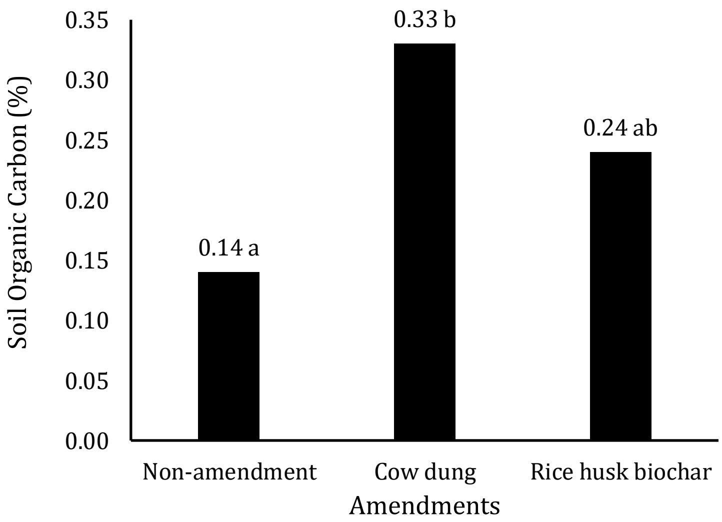

Figure 1. Effect of mycorrhizal, soil amendments, and inorganic fertilizers on soil organic carbon in Psamments
Remarks: Means in a column followed by the same letters show no significant difference in the DMRT test at a 5% significance level.

Glomalin Related Soil Protein (GRSP)

GRSP consists of easily extracted glomalin (EE-GRSP) (the latest glomalin fraction) and total-GRSP (the number of old and most recent fractions) (Wright and Upadhyaya, 1998; Rillig 2004; Liu et al. 2020), it is protein-bound soil which is a product of the turnover of hyphal mycelium during mycorrhizal activity (Balami et al., 2020). Recently, the T-GRSP was divided into easily extract glomalin (EE-GRSP) and difficult extract glomalin (DEG), but only T-GRSP and EE-GRSP were measured in this research. It means that EE-GRSP is a component of T-GRSP and build it up.

F test results showed that mycorrhizal treatment, soil amendments, and inorganic fertilizer had a significant effect on easily extracted glomalin (EE-GRSP) (P=0,000**) and T-GRSP (P=0.042 *). Application of mycorrhizal (6 spores/pot) with cow dung (M2P1A0) gave the best EE-GRSP (0.29 mg g^{-1}). Interaction of mycorrhizal 6 spores/pot, cow dung, and inorganic fertilizer (M1P1A1) was the highest T-GRSP (0.34 mg g^{-1}), increase up to 4.25 times than M0P0A0 that having the lowest value of EE-GRSP (0.05 mg g^{-1}) and T-GRSP (0.08 mg g^{-1}).

Syamsiyah et al. (2018) mentioned that glomalin as an organic-C deposit in the soil due to its long lifetime in soil, it also contains organic-C as the main binding (Li et al., 2020) material that stabilizes soil. Glomalin contained in the spore walls and hyphal when turnover during fungal activity as the main mechanism for glomalin deposition to the soil also describes the functionality of glomalin away from the hyphal wall to the soil during the life of fungal mycelium (Singh, 2012). The highest EE-GRSP was found in mycorrhizal treatment (6 spores/pot) with cow dung (M2P1A0) with an increase of 5.8 times compared to control (Table 1). Total GRSP was highest in mycorrhizal treatment (3 spores/pot), cow dung, inorganic fertilizer (M1P1A1) with a 4.4 times increase compared to controls (Table 1). Syamsiyah et al. (2018) reported that mycorrhizal application increases available and total glomalin. Increased glomalin caused by mycorrhizal hyphae which are inoculated into the soil will produce a compound in the form of glycoprotein known as glomalin (Rillig, 2004).

Table 1. Effect of mycorrhizal, soil amendments and inorganic fertilizers on easily extracted and total glomalin in Psamments

Treatments	Easily Extracted Glomalin **(EE-GRSP)**	Total glomalin related soil protein **(T-GRSP)**
	mg g^{-1}	
Control	0,05 ^{j}	0,08 ^{e}
No Mycorrhizal-Cow dung-Non fertilizer	0,16 ^{de}	0,3 ^{a}
No Mycorrhizal-RHB-No fertilizer	0,06 ^{j}	0,15 ^{bcde}
Mycorrhizal 3 spores -No Amendment-No fertilizer	0,14 ^{defg}	0,21 ^{abcde}
Mycorrhizal 3 spores -Cow dung -No fertilizer	0,22 ^{bc}	0,29 ^{ab}
Mycorrhizal 3 spores -RHB -No fertilizer	0,06 ^{j}	0,11 ^{de}
Mycorrhizal 6 spores - No Amendment -No fertilizer	0,08 ^{ghij}	0,26 ^{abc}
Mycorrhizal 6 spores – Cow dung -No fertilizer	0,29 ^{a}	0,3 ^{a}
Mycorrhizal 6 spores - RHB -No fertilizer	0,07 ^{hij}	0,09 ^{e}
No Mycorrhizal-No Amendment-100 kg ha^{-1} inorganic fertilizer	0,07 ^{ij}	0,08 ^{e}
No Mycorrhizal-Cow dung-100 kg ha^{-1} inorganic fertilizer	0,27 ^{ab}	0,31 ^{a}
No Mycorrhizal-RHB-100 kg ha^{-1} inorganic fertilizer	0,14 ^{def}	0,11 ^{de}
Mycorrhizal 3 spores-No Amendment-100 kg ha^{-1} inorganic fertilizer	0,12 ^{efghi}	0,13 ^{cde}
Mycorrhizal 3 spores-Cow dung-100 kg ha^{-1} inorganic fertilizer	0,17 ^{cd}	0,34 ^{a}
Mycorrhizal 3 spores-RHB-100 kg ha^{-1} inorganic fertilizer	0,09 ^{ij}	0,11 ^{de}
Mycorrhizal 6 spores-No Amendment-100 kg ha^{-1} inorganic fertilizer	0,07 ^{ij}	0,09 ^{de}
Mycorrhizal 6 spores-Cow dung-100 kg ha^{-1} inorganic fertilizer	0,1 ^{fghij}	0,23 ^{abcd}
Mycorrhizal 6 spores-RHB-100 kg ha^{-1} inorganic fertilizer	0,13 ^{defgh}	0,13 ^{cde}

Remarks: Means in a column followed by the same letters show no significant difference in the DMRT test at a 5% significance level.

Prasad and Kothari (2022) revealed that cow-dung treatment gives high glomalin value because it increases soil nutrition and biological activity, produces growth stimulating substances that cause mycorrhizal hyphae to develop and glomalin as adhesive and hyphae protector (Driver et al., 2005). GRSP with organic carbon and nitrogen in the soil is a source of nutrients available for plants that are very important for nutrient cycles and ecosystems (Treseder and Turner, 2007). McClellan et al. (2022) also mentioned that GRSP operationally defined protein fraction of soil organic matter, that hypothesized to build up contribution to long-term soil aggregation, soil stability, and also long-term soil carbon storage and it means the content of glomalin was affected especially by SOC and SOC itself significantly correlates with GT.

Microbial Biomass Carbon (MBC)

F test results showed that the interaction of mycorrhizal, soil amendments, and inorganic fertilizer significantly influenced microbial biomass carbon (P=0,000**). Microbial biomass carbon was the highest in mycorrhizal treatment (6 spores/pot) with biochar rice husk without inorganic fertilizer with a 23-fold increase in control (Figure 2). Mycorrhizal treatment (6 spores/pot), cow dung, and inorganic fertilizer (M2P1A1) increased the level of C-microbial biomass up to 11 times than the control (Figure 2).

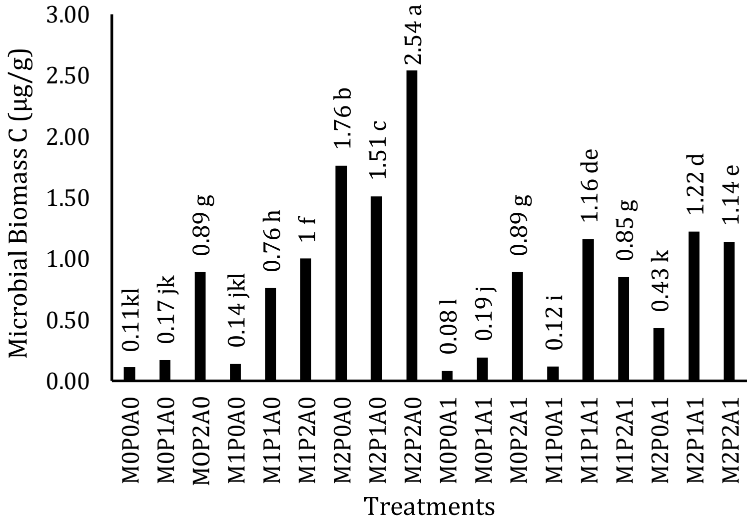

Figure 2. Effect of mycorrhizal, soil amendments, and inorganic fertilizers on carbon microbial biomass in Psamments
Remarks: Means in a column followed by the same letters show no significant difference in the DMRT test at a 5% significance level. M0= 0 spore/pot, M1= 3 spores/pot, M2=6 spores/pot (M2), P0= without amendment, p1=cow dung 60 t ha^{-1}, P2= rice husk biochar (RHB) 25 t ha^{-1}, A0= 0 kg ha-1, A1 = 100 kg ha^{-1} NPK fertilizer (15:15:15).

Fungal hyphae have a strong interaction with soil microbes (Nichols, 2008; Eddiwal et al., 2018;) along with the addition of biochar rice husk and inorganic fertilizer (Fang et al., 2021) as a source of nutrition for microbial development so that the decomposition process will be faster. Xu et al. (2014) suggested that biochar rice husk application affects soil bacterial community through improving the soil physicochemical characteristics. In line with Xu et al. (2016), the utilization of biochar derived from rice husk in soil has been found to enhance microbial activity, potentially attributed to the presence of labile carbon compounds inside the biochar. This, in turn, leads to an increase in the availability of nitrogen in soils subjected to biochar treatments. Some research result showed that the plant roots have the capacity to facilitate the establishment of some specific consortium of microorganisms while the rhizosphere were invaded by fungi (mycorrhizal), so that will be some association between microorganisms and root surfaces (rhizosphere) and gave some beneficial advantages to both plant and microorganisms (Berendsen et al. 2012; Huang et al. 2019; Gregory, 2022).

Conversely, the presence of increased microbial activity suggests a potential elevation in the rate at which nutrients, such as nitrogen, are cycled. This might potentially lead to a decrease in nitrogen leaching when rice husk biochar is applied. Prasasti and Purwani (2013) revealed that the increase in mycorrhizal dose showed an increase in mycorrhizal colonization. Thus, the extension of mycorrhizal hyphae causes interactions with various rhizobacterium (Sutariati and dan Wahab, 2012) and the population is increasing along with the application of biochar rice husk as an organic material containing organic carbon, humic acid, fulvic acid, and various other nutrients (N, P, K) which are a source of energy for soil microbes to accelerate decomposition and other chemical reaction processes that require microbial assistance.

Xu et al. (2016) also mentioned that biochar rice husk application may develop biogeochemical interfaces (BGIs) through the high porosity and various functional benefits. Hanzel et al. (2013) explained that BGI conditions to the soil could enhance the diversity of niche microhabitats in the soil, hence promoting the formation of diverse bacterial populations and facilitating various biological activities. Bi et al. (2018) explained that arbuscular mycorrhizal inoculation significantly improves the rhizosphere environment for microbes (rhizobacterium) to survive and adapt in the environment, so conducive to soil quality improvement and impact the growth of plants. Thereby MBC is in line with bacterial diversity that would be higher in biochar applications.

Effects of mycorrhizal, soil amendments, and inorganic fertilizers on root infection in Psamments

The analysis of varian results showed that mycorrhizal application with amendments and inorganic fertilizers significantly affected the percentage of root infections (p = 0,000**). The highest root infection was found in mycorrhizal treatment (6 spores/plants). It's about a 100% percentage of infection (Figure 3 and 4). Amending and adding mycorrhizal doses increase the percentage of root infections. In line with Bi et al. (2018) that mycorrhizal treatment gives a higher mycorrhizal colonization rate inside the root cell than non-inoculated (control) treatment. Ning et al. (2019) also reported that mycorrhizal treatment improves colonization rate than non-inoculated treatments. Prayudyaningsih and Sari (2016) research results showed that the roots of the host plant which were inoculated with mycorrhizal were infected, while the roots that were not inoculated did not indicate infection. The research results of Chiomento et al. (2022) also revealed the best root infectivity in treatments that were given higher mycorrhizal doses, while the lowest infectivity at the lower dose treatment roots. The extension of colonized hyphae mycorrhiza causes interactions with various rhizobacterium and soil microbes (Nichols, 2008; Eddiwal et al., 2018) which helps mycorrhizal signaling process such as mycorrhization helper bacteria (MHB) and phosphate solubilizing bacteria (PSB) so that it affects the mycorrhizal activity to colonize the roots (Gundale and DeLuca, 2007).

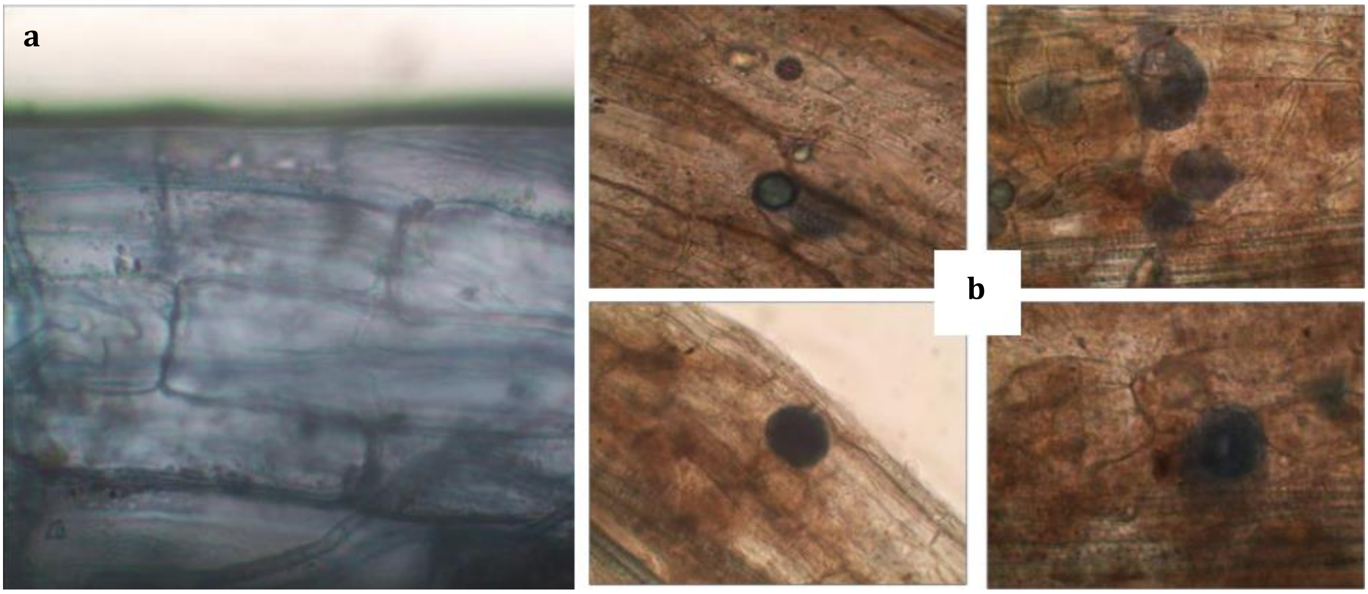

Figure 3. The lowest root infection without mycorrhizal treatment (M0P0A0) (a) and the highest root infection on mycorrhizal 6 spores/pot (M2P0A0) (b)

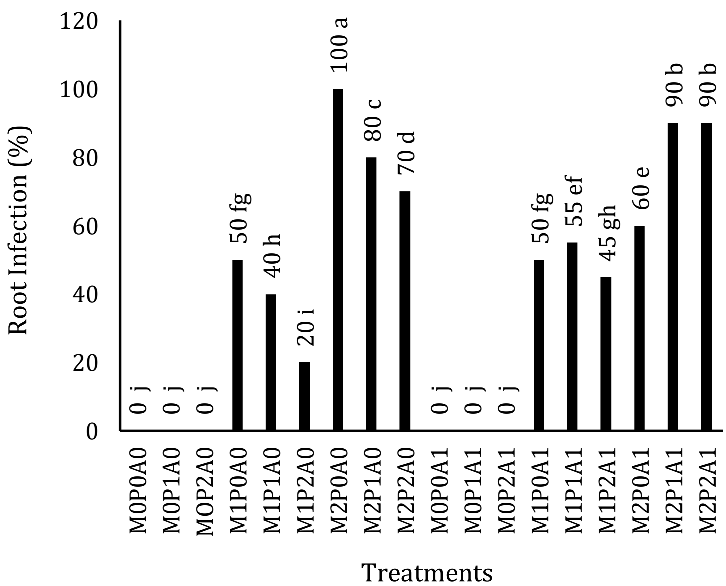

Figure 4. Effect of mycorrhizal, soil amendments, and inorganic fertilizers on root infection in Psamments
Remarks: Means in a column followed by the same letters show no significant difference in the DMRT test at a 5% significance level. M0= 0 spore/pot, M1= 3 spores/pot, M2=6 spores/pot (M2), P0= without amendment, p1=cow dung 60 t ha^{-1}, P2= rice husk biochar (RHB) 25 t ha^{-1}, A0= 0 kg ha-1, A1 = 100 kg ha^{-1} NPK fertilizer (15:15:15).

Correlation between SOC, GRSP, MBC, and Root Infection

Correlation test results showed that the parameters relate to mycorrhizal treatment, soil amendments and inorganic fertilizers. A significant correlation between EE-GRSP and soil organic carbon levels (r =0.467**) (Figure 5). A significant positive correlation was observed between EE-GRSP and T-Glomalin (r =0.695**) (Figure 6). The microbial biomass carbon parameter has a very strong correlation with the parameters of root infection (r = 0.488**) (Figure 7). All of these correlations are calculated by the ordinary least square method.

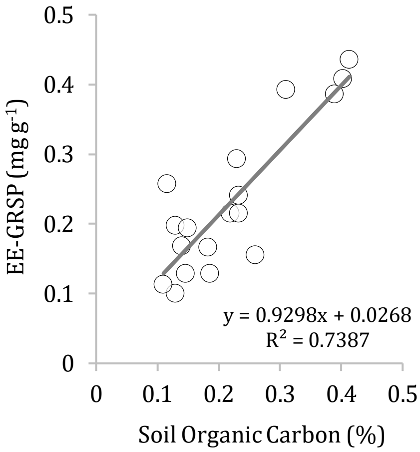

Figure 5. Relation between easily extracted glomalin and soil organic carbon

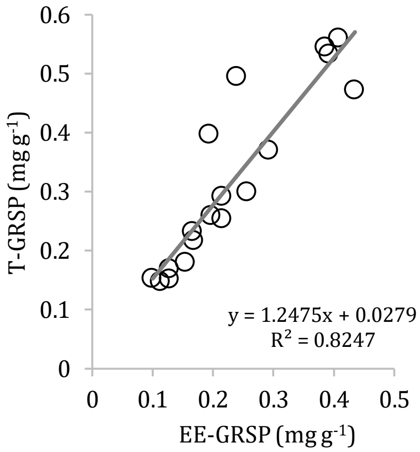

Figure 6. Relation between easily extracted glomalin and total glomalin

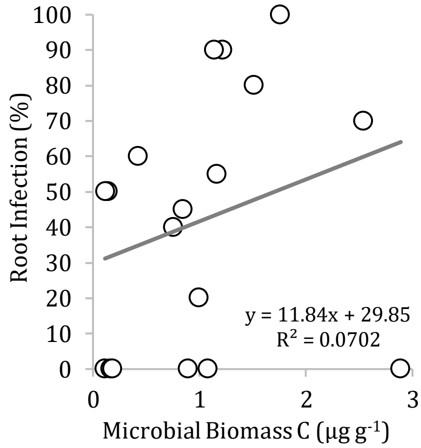

Figure 7. Relation between microbial biomass carbon and root infection

Balami et al. (2020) was reported that carbon in glomalin has a major contribution to increasing SOC (Matos et al. 2022) and has an impact on improving soil for crop production. Singh (2012) also explained that mycorrhizal and GRSP correlate with each other due to their role in building up aggregation then affecting SOC dynamics around the agroecosystem. MVA through its external roots will produce compounds in the form of glomalin glycoprotein and organic acids that can increase SOC levels so that there was a strong positive correlation between glomalin and SOC (Wang et al., 2018). In their study, Wu et al. (2022) report that the application of mycorrhizae has been found to enhance litter decomposition in laboratory trials of short duration. However, it is suggested that these effects may potentially yield beneficial long-term outcomes for soil organic carbon (SOC) accumulation, hence contributing to soil carbon storage. Its short-term effects knew that mycorrhizal vesicular-arbuscular (MVA) enhance the degradation of soil organic matter (SOM) by stimulating decomposers, and moreover the microbial metabolites never lost but they turn into highly stable compounds known as mineral-associated SOM fractions which will be the longest mean residence time in soil. Organic matter sub-soil contains more microbes derived compounds than top-soil and this microbial processes sugar seems to be better associated with mineral phases compared to plant-derived organic matter (Rumpel and Kögel-Knabner, 2011). Thereby, this mechanism which holds particular importance in the sub-soil (clay-minerals presence and sesquioxides) enhancement, represents a considerable potential for mineral-associated organic matter in long-term stabilization (Wu et al., 2022). There was a strong correlation between total and easily extracted glomalin due to their arrangement for presence in the rhizosphere (McClellan et al., 2022).

The findings of this research align with the statement of Spedding et al. (2004) that the activity and density of microbial populations in the soil are determined by changes in the chemical and physical conditions of soil. That is because the extension of mycorrhizal hyphae causes interactions with various rhizobacterium (Budiastuti et al., 2021) and soil microbes (Sodiq et al., 2021). The same statement by (Kilowasid et al., 2021) along with the increase in mycorrhizal dose shows an increase in mycorrhizal colonization. Soil microbes biomass carbon was measured to estimate the presence of microbacterial communities around the rhizosphere by measuring the microbe's organic carbon molecules (Ashraf et al., 2020). There was a microbe that colonized and resided in the root (surrounding rhizosphere) that utilizes its exudates to their metabolism and also a role as a beneficial agent to the plant due to these microbes function (fixation of nitrogen, nutrient uptake enhancement, suppression of plant from diseases) and they called as plant growth promoting rhizobacteria (PGPR) (Kumari et al., 2018).

Microbial biomass carbon demonstrated a very significant correlation with root infection, which agrees with our findings. Living root inputs are more effective than litter inputs in producing fast and slow-cycling SOC, as well as being more efficiently utilized by the soil microbial population, leading to an increase in the pool of mineral-associated SOC (Sokol et al., 2019). This is consistent with the theory of a dissolved organic C route from live roots to microbial biomass, as well as mineral-associated SOC (Cotrufo et al., 2019). The type of mycorrhizal association determines the formation of slow-cycling soil carbon, microbial stabilization which increases with soil depth, secretions and microbial necromass could potentially supplied carbon inputs for mineral-associated soil organic C formation, while C released by roots at deep can be stabilized and contribute to C pool. The presence of roots can enhance the availability of labile carbon to rhizosphere bacteria, resulting in higher rates of SOM mineralization, roots can also contribute to the destabilization by exposing previously protected carbon to decomposition of microbial (Dijkstra et al., 2021). Roots have a substantial impact on the mineralization of soil organic matter, nitrification, and subsequent immobilization driven by microbial. The presence of roots speeds up the decomposition of SOM by up to five times (Gregory, 2022). These findings point to the importance of mycorrhizal fungi in microbial biomass, soil organic carbon, and root infection to improve the Psamments characteristics.

Conclusion

Psamments have low fertility, especially in the concentration of soil organic carbon, total nitrogen, cation exchange capacity, available phosphor, and available potassium, according to the initial soil analysis and soil fertility category. Adding mycorrhizal, soil amendments, and NPK fertilizers could enhance the problem. Based on the results obtained, several conclusions were drawn that the adding of mycorrhizal, amendments and inorganic fertilizers can increase the MBC (M2P1A1) with an 11-fold increase (1.22 μg/g) than non-mycorrhizal treatment. Mycorrhizal (6 spores/pot) with cow-dung (M2P1A0) gave the best EE-GRSP (0.29 mg g^{-1}), and the highest root infection was found in mycorrhizal treatment (6 spores/pot) with a percentage of infection of 100%. A very strong correlation occurs between EE-GRSP and soil organic carbon, EE-GRSP and T-Glomalin; and also microbial biomass carbon and root infection. Mycorrhizal associations are vital for microbial stability; C produced by roots contributes to C storage. Roots could boost the availability of labile carbon to rhizosphere microorganisms, resulting in faster SOM mineralization and SOC stabilization. Soil microbial activities, such as the mineralization of soil organic matter, are influenced considerably by roots. SOM decomposition speeds up when roots are present. These data imply that mycorrhizal fungi play a key role in microbial biomass, soil organic carbon, and root infection. This study showed that combining mycorrhizal fungi with soil amendments and inorganic fertilizers can enhance the properties of Psamments.

Acknowledgement

This research was supported by LPPM Universitas Sebelas Maret, Surakarta through Fundamental Research Grant 2019. We also said thanks to the Department of Soil Science, Faculty of Agriculture, Universitas Sebelas Maret for kindly helping with this research and the facility of laboratory.

References

Alfahmi, F., Boer, R., Hidayat, R., Perdinan, Sopaheluwakan, A., 2019. The impact of concave coastline on rainfall offshore distribution over Indonesian maritime continent. *Scientific World Journal* Article ID 6839012.

Ashraf, M. N., Hu, C., Wu, L., Duan, Y., Zhang, W., Aziz, T., Cai, A., Abrar, M.M., Xu, M., 2020. Soil and microbial biomass stoichiometry regulate soil organic carbon and nitrogen mineralization in rice-wheat rotation subjected to long-term fertilization. *Journal of Soils and Sediments* 20(8): 3103–3113.

Azadi, H., Ho, P., Hasfiati, L. 2011. Agricultural land conversion drivers: A comparison between less developed, developing and developed countries. *Land Degradation and Development* 22(6): 596-604.

Bai, Y., Pan, B., Charles, T.C., Smith, D.L., 2002. Co-inoculation dose and root zone temperature for plant growth promoting rhizobacteria on soybean [Glycine max (L.) Merr] grown in soil-less media. *Soil Biology and Biochemistry* 34(12): 1953–1957.

Baiamonte, G., Crescimanno, G., Parrino, F., De Pasquale, C., 2021. Biochar amended soils and water systems: Investigation of physical and structural properties. *Applied Sciences* 11(24): 12108.

Balami, S., Vašutová, M., Godbold, D., Kotas, P., Cudlín, P., 2020. Soil fungal communities across land use types. *IForest-Biogeosciences and Forestry* 13(6): 548-558.

Berendsen, R.L., Pieterse, C.M.J., Bakker, P.A.H.M., 2012. The rhizosphere microbiome and plant health. *Trends in Plant Science* 17(8): 478-486.

Bi, Y., Zhang, Y., Zou, H., 2018. Plant growth and their root development after inoculation of arbuscular mycorrhizal fungi in coal mine subsided areas. *International Journal of Coal Science and Technology* 5(1): 47–53.

Black, C.A., Evans, D.D., White, J.L., Ensminger, L.E., Clark, F.E., 2016. Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties. Soil Science Society of America. Madison, Wisconsin, USA. 1159p.

Budiastuti, M.T.S., Purnomo, D., Supriyono, Pujiasmanto, B., Setyaningrum, D., 2020. Effects of light intensity and co-inoculation of arbuscular mycorrhizal fungi and rhizobium on root growth and nodulation of Indigofera tinctoria. *SAINS TANAH - Journal of Soil Science and Agroclimatology* 17(2): 94-99.

Cheng, X.F., Xie, M.M., Li, Y., Liu, B.Y., Liu, C.Y., Wu, Q.S., Kuča, K., 2022. Effects of field inoculation with arbuscular mycorrhizal fungi and endophytic fungi on fruit quality and soil properties of Newhall navel orange. *Applied Soil Ecology* 170: 104308.

Chiomento, J.L.T., Filippi, D., Krasnievicz, G.M., De Paula, J.E.C., Fornari, M., Trentin, T.S., 2022. Arbuscular mycorrhizal fungi potentiate the root system and the quality of goldenberry fruits. *Advances in Horticultural Science* 36(4), 265–273.

Clausing, S., Polle, A., 2020. Mycorrhizal phosphorus efficiencies and microbial competition drive root P uptake. *Frontiers in Forests and Global Change 3*(1): 54.

Cotrufo, M.F., Ranalli, M.G., Haddix, M.L., Six, J., Lugato, E., 2019. Soil carbon storage informed by particulate and mineral-associated organic matter. *Nature Geoscience* 12(12): 989–994.

Dijkstra, F.A., Zhu, B., Cheng, W., 2021. Root effects on soil organic carbon: a double-edged sword. *New Phytologist 230*(1): 60–65.

Driver, J.D., Holben, W.E., Rillig, M.C., 2005. Characterization of glomalin as a hyphal wall component of arbuscular mycorrhizal fungi. *Soil Biology and Biochemistry* 37(1): 101-106.

Ebido, N.E., Edeh, I.G., Unagwu, B.O., Nnadi, A.L., Ozongwu, O.V., Obalum, S.E., Igwe, C.A., 2021. Rice-husk biochar effects on organic carbon, aggregate stability and nitrogen-fertility of coarse-textured Ultisols evaluated using Celosia argentea growth. *Sains Tanah-Journal of Soil Science and Agroclimatology* 18(2): 177–187.

Eddiwal, E., Saidi, A., Husin, E.F., Rasyidin, A., 2018. Pengaruh inokulasi fungi mikoriza arbuskula (FMA) plus organik terhadap pertumbuhan dan produksi jagung pada Ultisol. *Jurnal Solum – Journal of Soil and Land Utilization Management* 15(2): 50-59. [in Indonesian]

Fang, H., Liu, K., Li, D., Peng, X., Zhang, W., Zhou, H., 2021. Long-term effects of inorganic fertilizers and organic manures on the structure of a paddy soil. *Soil and Tillage Research* 213: 105137.

FAO, 2021. Standard operating procedure for soil nitrogen: Kjeldahl method. Rome, Italy. 25p. Available at [Access date: 15.07.2023]: https://www.fao.org/3/cb3642en/cb3642en.pdf

Fitriatin, B.N., Amanda, A.P., Kamaluddin, N.N., Khumairah, F.H., Sofyan, E.T., Yuniarti, A., Turmuktini, T., 2021. Some soil biological and chemical properties as affected by biofertilizers and organic ameliorants application on paddy rice. *Eurasian Journal of Soil Science* 10(2): 105–110.

Goebel, M.O., Bachmann, J., Reichstein, M., Janssens, I.A., Guggenberger, G., 2011. Soil water repellency and its implications for organic matter decomposition - is there a link to extreme climatic events? *Global Change Biology* 17(8): 2640-2656.

Gregory, P.J., 2022. RUSSELL REVIEW Are plant roots only "in" soil or are they "of" it? Roots, soil formation and function. *European Journal of Soil Science* 73(1): e13219.

Gundale, M.J., DeLuca, T.H., 2007. Charcoal effects on soil solution chemistry and growth of Koeleria macrantha in the ponderosa pine/Douglas-fir ecosystem. *Biology and Fertility of Soils* 43(3): 303–311.

Handika, G., Yudono, P., Rogomulyo, R., 2016. Pengaruh waktu penyiangan terhadap pertumbuhan dan hasil kacang hijau (Vigna radiata (L .) R . Wilczek) di lahan pasir pantai Samas Bantul. *Vegetalika* 5(4): 25–36. [in Indonesian]

Hanzel, J., Myrold, D., Sessitsch, A., Smalla, K., Tebbe, C.C., Totsche, K.U., 2013. Microbial ecology of biogeochemical interfaces – diversity, structure, and function of microhabitats in soil. *FEMS Microbiology Ecology* 86(1): 1-2.

Hapsoh, Gusmawartati, Amri, A.I., Diansyah, A., 2017. Respons pertumbuhan dan produksi tanaman cabai keriting (Capsicum annuum L.) terhadap aplikasi pupuk kompos dan pupuk anorganik di polibag. *Jurnal Hortikultura Indonesia* 8(3): 203–208. [in Indonesian]

He, J.D., Chi, G.G., Zou, Y.N., Shu, B., Wu, Q.S., Srivastava, A.K., Kuča, K., 2020. Contribution of glomalin-related soil proteins to soil organic carbon in trifoliate orange. *Applied Soil Ecology* 154: 103592.

Herviyanti, Maulana, A., Lita, A.L., Prasetyo, T.B., Monikasari, M., Ryswaldi, R., 2022. Characteristics of inceptisol ameliorated with rice husk biochar to glyphosate adsorption. *SAINS TANAH - Journal of Soil Science and Agroclimatology* 19(2): 230–240.

Hodge, A., Fitter, A.H., 2010. Substantial nitrogen acquisition by arbuscular mycorrhizal fungi from organic material has implications for N cycling. *PNAS- Proceedings of the National Academy of Sciences of the United States of America* 107(31): 13754-13759.

Huang, A. C., Jiang, T., Liu, Y. X., Bai, Y. C., Reed, J., Qu, B., Goossens, A., Nützmann, H.W., Bai, Y., Osbourn, A., 2019. A specialized metabolic network selectively modulates Arabidopsis root microbiota. *Science* 364(6440): eaau6389.

Husein, H. H., Lucke, B., Bäumler, R., Sahwan, W., 2021. A contribution to soil fertility assessment for arid and semi-arid lands. *Soil Systems* 5(3): 42.

Kelland, M. E., Wade, P. W., Lewis, A. L., Taylor, L. L., Sarkar, B., Andrews, M. G., Lomas, M.R., Cotton, T.E.A., Kemp, S.J., James, R.H., Pearce, C.R., Hartley, S.E., Hodson, M.E., Leake, J.R., Banwart, S.A., Beerling, D.J., 2020. Increased yield and CO2 sequestration potential with the C4 cereal Sorghum bicolor cultivated in basaltic rock dust-amended agricultural soil. *Global Change Biology* 26(6): 3658-3676.

Kilowasid, L. M. H., Sanjaya, M. F., Sabaruddin, L., Hasid, R., Sulaeman, D., Nurmas, A., 2021. The use of soil biostructures created by soil fauna ecosystem engineers fed with different organic materials as inoculum source of arbuscular mycorrhiza fungi on cocoa seedling. *SAINS TANAH - Journal of Soil Science and Agroclimatology* 18(2): 166–176.

Kumari, P., Meena, M., Upadhyay, R.S., 2018. Characterization of plant growth promoting rhizobacteria (PGPR) isolated from the rhizosphere of Vigna radiata (mung bean). *Biocatalysis and Agricultural Biotechnology* 16: 155–162.

Li, X., Han, S., Luo, X., Chen, W., Huang, Q., 2020. Arbuscular mycorrhizal-like fungi and glomalin-related soil protein drive the distributions of carbon and nitrogen in a large scale. *Journal of Soils and Sediments* 20(2): 963–972.

Liu, H., Wang, X., Liang, C., Ai, Z., Wu, Y., Xu, H., Xue, S., Liu, G., 2020. Glomalin-related soil protein affects soil aggregation and recovery of soil nutrient following natural revegetation on the Loess Plateau. *Geoderma* 357: 113921.

Matos, P.S., da Silva, F.C., Pereira, M.G., da Silva, E.M.R., Tarré, R.M., Franco, C.A.L., Zonta, E., 2022. Short-term modifications of mycorrhizal fungi, glomalin and soil attributes in a tropical agroforestry. *Acta Oecologica* 114: 103815.

McClellan, S. A., Laws, E. A., Elsey-Quirk, T., 2022. Estimates of protein in coastal marsh soils: A case study of the utility of the Bradford assay for quantifying soil protein. *Geoderma* 410: 115676.

Meftah, O., Guergueb, Z., Braham, M., Sayadi, S., Mekki, A., 2019. Long term effects of olive mill wastewaters application on soil properties and phenolic compounds migration under arid climate. *Agricultural Water Management* 212: 119-125.

Nichols, K.A., 2008. Indirect contributions of AM fungi and soil aggregation to plant growth and protection. In: Mycorrhizae: Sustainable Agriculture and Forestry. Siddiqui, Z.A., Akhtar, M.S., Futai, K. (Eds.). Springer, Dordrecht. pp 177–194.

Ning, Y., Xiao, Z., Weinmann, M., Li, Z., 2019. Phosphate uptake is correlated with the root length of celery plants following the association between arbuscular mycorrhizal fungi, Pseudomonas sp. and biochar with different phosphate fertilization levels. *Agronomy* 9(12): 824.

Nurmalasari, A. I., Supriyono, S., Sri Budiastuti, M.T., Sulistyo, T.D., Nyoto, S., 2021. Composting of rice straw for organic fertilizer and manufacturing rice husk charcoal as planting medium in soybean demonstration plot. *PRIMA - Journal of Community Empowering and Services* 5(2): 102–109.

Page, A.L., Miller, R.H., Keeney, D.R., 1982. Methods of Soil Analysis Part 2: Chemical and Microbiological Properties. 2nd Ed. American Society of Agronomy - Soil Science Society of America, Madison, Wisconsin USA. 1159 p.

Pakbaz, M.S., Behzadipour, H., Ghezelbash, G.R., 2018. Evaluation of shear strength parameters of sandy soils upon microbial treatment. *Geomicrobiology Journal* 35(8): 721-726.

Paterson, E., Sim, A., Davidson, J., Daniell, T.J., 2016. Arbuscular mycorrhizal hyphae promote priming of native soil organic matter mineralisation. *Plant and Soil* 408(1–2): 243-254.

Phillips, J.M., Hayman, D.S., 1970. Improved procedures for clearing roots and staining parasitic and vesicular-arbuscular mycorrhizal fungi for rapid assessment of infection. *Transactions of the British Mycological Society* 55(1): 158-161.

Prasad, A., Kothari, N., 2022. Cow products: boon to human health and food security. *Tropical Animal Health and Production* 54(1): 12.

Prasasti, O.H., Purwani, K.I., 2013. Pengaruh mikoriza Glomus fasciculatum terhadap pertumbuhan vegetatif tanaman kacang tanah yang terinfeksi patogen Sclerotium rolfsii. *Jurnal Sains Dan Seni Pomits* 2(2): 74–78. [in Indonesian]

Prayudyaningsih, R., Sari, R., 2016. The application of arbuscular mycorrhizal fungi (AMF) and compost to improve the growth of teak seedlings (Tectona grandis Linn. f.) on limestone post-mining Soil. *Jurnal Penelitian Kehutanan Wallacea* 5(1): 37–46.

Rillig, M.C., 2004. Arbuscular mycorrhizae, glomalin, and soil aggregation. *Canadian Journal of Soil Science* 84(4): 355-363.

Rondhi, M., Pratiwi, P.A., Handini, V.T., Sunartomo, A.F., Budiman, S.A., 2018. Agricultural land conversion, land economic value, and sustainable agriculture: A case study in East Java, Indonesia. *Land 7*(4): 148.

Rumpel, C., Kögel-Knabner, I., 2011. Deep soil organic matter-a key but poorly understood component of terrestrial C cycle. *Plant and Soil* 338(1):143-158.

Safitri, D.R., Sihaloho, E.D., 2020. Lumbung padi Indonesia dan kemiskinan: studi kasus kabupaten kota di Jawa Timur. *Ekonomis: Journal of Economics and Business* 4(1): 56-61. [in Indonesian]

Saleem, H., Ahmad, M., Rashid, J., Ahmad, M., Al-Wabel, M.I., Amin, M., 2022. Carbon potentials of different biochars derived from municipal solid waste in a saline soil. *Pedosphere* 32(2): 283–293.

Sharma, N., Shukla, Y.R., Singh, K., Mehta, D.K., 2020. Soil fertility, nutrient uptake and yield of bell pepper as influenced by conjoint application of organic and inorganic fertilizers. *Communications in Soil Science and Plant Analysis* 51(20): 1626–1640.

Singh, P.K., 2012. Role of glomalin related soil protein produced by arbuscular mycorrhizal fungi : A Review. *Agricultural Science Research Journal* 2(3): 119-125.

Sitko, N.J., Jayne, T.S., 2014. Structural transformation or elite land capture? The growth of "emergent" farmers in Zambia. *Food Policy* 48: 194-202.

Sodiq, A.H., Setiawati, M.R., Santosa, D.A., Widayat, D., 2021. Molecular identification of isolates from local microorganisms as potential biofertilizer. *SAINS TANAH - Journal of Soil Science and Agroclimatology 18*(2): 188–193.

Soil Survey Staff, 2022. Kellogg Soil Survey Laboratory methods manual. Soil Survey Investigations Report No. 42, Version 6.0. Part 1: Current Methods. U.S. Department of Agriculture, Natural Resources Conservation Service, USA. Available at [Access date: 15.07.2023]: https://www.nrcs.usda.gov/sites/default/files/2023-01/SSIR42.pdf

Sokol, N.W., Kuebbing, S.E., Karlsen-Ayala, E., Bradford, M.A., 2019. Evidence for the primacy of living root inputs, not root

or shoot litter, in forming soil organic carbon. *New Phytologist* 221(1): 233–246.
Spedding, T.A., Hamel, C., Mehuys, G.R., Madramootoo, C.A., 2004. Soil microbial dynamics in maize-growing soil under different tillage and residue management systems. *Soil Biology and Biochemistry* 36(3): 499-512.
Samuel, S.S., Veeramani, A., 2021. Advantages of arbuscular mycorrhizal fungi (AMF) production for the profitability of agriculture and biofertilizer industry. In: Mycorrhizal Fungi - Utilization in Agriculture and Industry. Radhakrishnan, R. (Ed.). IntechOpen, pp. 31–46.
Sukartono, Kusumo, B.H., Suwardji, Bakti, A.A., Mahrup, Susilowati, L.E., Fahrudin, 2022. Influence of biochar amendments on the soil quality indicators of sandy loam soils under cassava–peanut cropping sequence in the semi-arid tropics of Northern Lombok, Indonesia. *SAINS TANAH - Journal of Soil Science and Agroclimatology 19*(2): 205–210.
Sun, J., Jia, Q., Li, Y., Zhang, T., Chen, J., Ren, Y., Dong, K., Xu, S., Shi, N.N., Fu, S., 2022. Effects of arbuscular mycorrhizal fungi and biochar on growth, nutrient absorption, and physiological properties of maize (Zea mays L.). *Journal of Fungi*, 8(12): 1275.
Supriyadi, Mustikaningrum, I.A., Herawati, A., Purwanto, P., Sumani, S., 2018. Soil quality assessment in organic and non organic paddy fields in Susukan, Indonesia. *Bulgarian Journal of Agricultural Science*, 24(5): 777–784.
Sutariati, G.A.K., dan Wahab, A., 2012. Karakter fisiologis dan kemangkusan rizobakteri indigenus Sulawesi Tenggara sebagai pemacu pertumbuhan tanaman cabai. *Jurnal Hortikultura* 22(1): 57–64. [in Indonesian]
Syamsiyah, J., Herawati, A., Mujiyo, 2018. The potential of arbuscular mycorrhizal fungi application on aggregrate stability in alfisol soil. *IOP Conference Series: Earth and Environmental Science* 142: 012045.
Torry, A., Kusumo, S., 2010. Optimization of the management and empowerment of the outer islands in order to maintain the integrity of the Republic of Indonesia. *Jurnal Dinamika Hukum* 10(3): 327–337. [in Indonesian]
Treseder, K.K., Turner, K.M., 2007. Glomalin in ecosystems. *Soil Science Society of America Journal* 71(4): 1257-1266.
Vance, E.D., Brookes, P.C., Jenkinson, D.S., 1987. An extraction method for measuring soil microbial biomass C. *Soil Biology and Biochemistry* 19(6): 703–707.
Vezzani, F.M., Anderson, C., Meenken, E., Gillespie, R., Peterson, M., Beare, M.H., 2018. The importance of plants to development and maintenance of soil structure, microbial communities and ecosystem functions. *Soil and Tillage Research* 175: 139-149.
Wang, Q., Li, J., Chen, J., Hong, H., Lu, H., Liu, J., Dong, Y., Yan, C. 2018. Glomalin-related soil protein deposition and carbon sequestration in the Old Yellow River delta. *Science of the Total Environment* 625: 619-626.
Wei, L., Vosátka, M., Cai, B., Ding, J., Lu, C., Xu, J., Yan, W., Li, Y., Liu, C., 2019. The role of arbuscular mycorrhiza fungi in the decomposition of fresh residue and soil organic carbon: A mini-review. *Soil Science Society of America Journal* 83(3): 511-517.
Wong, E.V.S., Ward, P.R., Murphy, D.V., Leopold, M., Barton, L., 2020. Vacuum drying water-repellent sandy soil: Anoxic conditions retain original soil water repellency under variable soil drying temperature and air pressure. *Geoderma* 372: 114385.
Wright, S.F., Upadhyaya, A., 1998. A survey of soils for aggregate stability and glomalin, a glycoprotein produced by hyphae of arbuscular mycorrhizal fungi. *Plant and Soil* 198: 97–107.
Wu, Y., Deng, M., Huang, J., Yang, S., Guo, L., Yang, L., Ahirwal, J., Peng, Z., Liu, W., Liu, L., 2022. Global patterns in mycorrhizal mediation of soil carbon storage, stability, and nitrogen demand: A meta-analysis. *Soil Biology and Biochemistry* 166: 108578.
Xu, H.J., Wang, X.H., Li, H., Yao, H.Y., Su, J.Q., Zhu, Y.G., 2014. Biochar impacts soil microbial community composition and nitrogen cycling in an acidic soil planted with rape. *Environmental Science and Technology* 48(16): 9391–9399.
Xu, N., Tan, G., Wang, H., Gai, X., 2016. Effect of biochar additions to soil on nitrogen leaching, microbial biomass and bacterial community structure. *European Journal of Soil Biology* 74: 1-8.