The use of soil ameliorants to improve soil quality and crop productivity of degraded semi-arid upland in Gunung Kidul, Yogyakarta, Indonesia

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Abstract. Optimization of degraded semi-arid upland needs to be done by improving soil fertility and quality, as well as increasing plant resistance to drought. The purpose of this research is to evaluate the effect of balanced fertilization and soil ameliorant on soil quality and crop productivity. The study was conducted on degraded semi-arid upland in Gunung Kidul Regency, Yogyakarta, Indonesia at the beginning of the dry season in 2018. Randomized block design with five treatments and four replications was applied. The treatments consisted of TP: control (farmer management), T1: Balanced fertilization recommendation, T2: T1+Biochar SP-50, T3: T1+Bio-silica, T4: T1+Biochar SP-50+Bio-silica, and T5: T1+Vulkanorf K-424. Soil ameliorant treatment had a positive effect on water aggregate stability. Treatment of Biochar SP-50 in combination with Bio-silica had a positive effect on soil bulk density, aeration pore, and water availability pore. Balanced fertilization accompanied by Biochar SP-50 (without and with bio-silica) gave a positive effect on the content of organic C and K-potential. Plant growth of balanced fertilization+Biochar SP-50 was significantly higher than other treatments, while maize production among treatments did not show a significant difference. Therefore, it requires long-term and continuous treatment to improve soil quality and crop productivity in degraded land.

1. Introduction

Semi-arid upland is land exposure that is never inundated in a year or all the time, with an annual rainfall of less than 2000 mm year⁻¹ and soil moisture regime classified as Ustic. Semi-arid upland area in Indonesia around 10.8 million ha, 48 percent of which are in West Nusa Tenggara and East Nusa Tenggara, the others are spread throughout the islands in Indonesia especially in the eastern region [1]. Rainfall is generally erratic, which occurs in a short time but in a relatively large amount, resulting in high rainfall intensity, so it's mostly raining lost as a surface run-off. Distribution of rain throughout the year is uneven, so only can be planted once [2].

Although water availability is a major limiting factor in semi-arid upland productivity, optimizing this land can not only be done by increasing water availability, but it must also be accompanied by increasing water use efficiency, which often becomes low because the soil has been degraded. Several research results
show very low soil quality on semi-arid upland that has been intensively cultivated, mainly characterized by very low levels of soil organic C [3-6]. The cause is a natural and land management factors, such as conventional farming systems and traditional farming patterns that often burn crop residues before the planting season [6]. In semi-arid upland, the amount of crop residue production especially in the off season is also very low [7]. However, on semi-arid upland that has applied conservation agriculture (minimum tillage, cover crops, rotation/intercropping), average of organic C content are in medium category [8].

Besides optimizing the use of crop residues and manure, the use of biochar can also improve soil quality. Several studies have shown the positive impact of biochar in improving soil quality i.e. the physical [9-14], chemical [15-18] and biological [19-22] properties of the soil. Improvements in soil properties that have an impact on increasing efficiency of water use are needed to overcome main limiting factor for agricultural development in semi-arid upland. Carvalho et al. [10] stated that application of biochar as a soil ameliorant can be a worthy strategy to guarantee yield stability under short-term water-limited conditions.

Improvement semi-arid upland productivity can also be conducted by increasing plant resistance to drought stress. One of the mechanisms for plant tolerance in response to drought stress is by increasing the performance of stomata to prevent water signals through leaves [23]. Silica (Si) gained more attentions where crops are able to contend drought as Si regulates stomata opening [24-26]. Si can be obtained from various natural sources, namely straw compost, rice husks, steel slag, and silica fertilizer [27 and 28]. In Indonesia, the abundant source of Si is the quartz mineral, which has very low solubility [29]. Santi et al. [30] formulated Bio-Nano OSA, a high available Si originating from quartz sand. The experiment results showed that application of bio silica on Alfisols Indramayu and Majalengka [26, 31] and Ultisols Lampung all in Indonesia region [31, 32] had a positive effect on nutrient and water use efficiency, as well as plant productivity. Volcanic ash is also a material with high silica content. The SiO₂ content in the volcanic ash of Merapi was around 55-56% [33, 34]. Combined treatment of volcanic ash from Merapi, cow manure and mineral soil (Inceptisols) has a significant effect on physico-chemical properties of plant growth media [34]. The use of soil ameliorant formulated from volcanic ash and compost also has a positive effect on improving soil physical properties, as well as growth and production of soybeans on upland in Taman Bogo, Lampung Province, Indonesia [35].

In general, the soil in semi-arid is classified as fertile [3, 4, 8]. However, balanced fertilization is still needed to be implemented so that plant productivity can be optimum. The purpose of this research is to study the effect of balanced fertilization and ameliorant on soil quality and crop productivity.

2. Materials and methods

2.1. Research location

This research was conducted on semi-arid upland with food crops base farming system in Bleberan Village, Playen District, Gunung Kidul Regency, Yogyakarta, Indonesia (110°53’33’’E - 7°96’34’’S), starting at the end of the rainy season (from May to September 2018). Soil characteristics (chemical and physical properties) are presented in Tables 1 and 2. Soil texture in this location is classified as silty clay having a neutral pH. Naturally, the soil characteristic is relatively fertile, as indicated by the very high base saturation, moderate cation exchange capacity (CEC), with high to very high exchangeable Ca and Mg. However, soil in the research location was degraded, indicated by low soil organic C content and very low organic N content. Soil organic matter is a key indicator of soil fertility. It is necessary to establish a relationship between SOM and productivity for different crops and soils in different regional contexts, so that soil organic matter targets can be set to achieve expected yields and sustainable agriculture [36].
Table 1. Soil chemical properties before treatment.

| Parameter                  | Analysis results | Class *) |
|----------------------------|------------------|----------|
| Texture                    |                  |          |
| Sand (%)                   | 8                |          |
| Silt (%)                   | 48               |          |
| Clay (%)                   | 44               |          |
| pH                         |                  |          |
| H₂O                        | 7.86             | Alkaline |
| KCl                        | 6.76             | Rather alkaline |
| Organic material:          |                  |          |
| C (%)                      | 1.19             | Low      |
| N (%)                      | 0.04             | Very Low |
| C/N                        | 29.57            | Very High |
| Extract HCl 25%:           |                  |          |
| P₂O₅ (mg 100 g⁻¹)         | 37.82            | Moderate |
| K₂O (mg 100 g⁻¹)          | 6.26             | low      |
| K₂O Morgan (mg kg⁻¹ P)     | 115.52           |          |
| Exchangeable Cation:       |                  |          |
| Ca (cmol(+) kg⁻¹)          | 63.68            | Very high |
| Mg (cmol(+) kg⁻¹)          | 4.39             | High     |
| K (cmol(+) kg⁻¹)           | 0.23             | Low      |
| Na (cmol(+) kg⁻¹)          | 0.46             | Moderate |
| CEC (cmol(+) kg⁻¹)         | 20.08            | Moderate |
| Base Saturation (%)        | >100             | Very High |

*) [38]

The results of the analysis of soil physical properties (Table 2) showed that the average of soil bulk density was <1 g cm⁻³, and the total pore space was moderate (56-58% volume). However, soil permeability was low (on average less than 2 cm hour⁻¹). The average aeration pore was less than 2% volume (very low) and available water pore less than 7% volume (low). Thus, the physical condition of the soil did not support the ability of the soil to store water. Poor soil physical conditions can be caused by low soil organic matter content.

Table 2. Soil physical properties before treatment.

| Block | Bulk Density (g cm⁻³) | Total pore | Drainage Pore | Water available pore | Permeability cm hour⁻¹ |
|-------|------------------------|------------|---------------|----------------------|------------------------|
|       |                        |            | Fast          | Slow                 |                        |
|       |                        |            | %             | %                    |                        |
| I     | 0.82                   | 58.14      | 12.42         | 6.00                 | 7.77                   | 2.29                   |
| II    | 0.88                   | 56.19      | 10.45         | 5.83                 | 6.02                   | 1.60                   |
| III   | 0.90                   | 57.30      | 9.89          | 3.87                 | 6.00                   | 2.04                   |
| Average | 0.87                 | 57.21      | 10.92         | 5.24                 | 6.60                   | 1.98                   |

The total rainfall in 2018 is 1,200 mm year⁻¹, with dry months (<100 mm month⁻¹) for 7 months occurred from February to October 2018 (Figure 1). According to Ritung et al. [1], areas with rainfall <2,000 mm
year\(^{-1}\) are classified as semi-arid climates. The results of the study by Khalimi and Kusuma [39] showed that the availability of water in the upland in Gunung Kidul was classified as a deficit.

![Rainfall in 2018 at the research location.](image)

**Figure 1.** Rainfall in 2018 at the research location.

2.2. Materials

Soil ameliorants used in the experiment were: (1) Biochar SP-50 which was formulated from rice husk biochar and manure compost, with the contents of C-organic, N, P\(_2\)O\(_5\), K\(_2\)O, CaO and MgO, 32.07, 1.75, 1.14, 1.54, 1.89 and 0.68% respectively [40], (2) Bio-silica, which was extracted from quartz sand, contains 5\% H\(_4\)SiO\(_4\) with a particle size of 18 nm and was combined with Si solvent microbes [30, 32] and (3) Volkanorf K-424, which was a soil ameliorant formulated from volcanic ash from Mt. Merapi in Yogyakarta and compost, with the contents of C-organic, N, P\(_2\)O\(_5\), K\(_2\)O, CaO and MgO, respectively 56.50, 0.95, 3.78, 0.62, 5.46 and 0.29% [37]. Inorganic fertilizers used were Phonska (NPK 15-15-15), Urea, SP-36, and KCl. Maize was used as the indicator crop.

2.3. Methods

The experiment used a randomized block design with six treatments and four replications. The treatments applied were: TP = farmer management as control, T1: balanced fertilization, T2: T1 + Biochar SP-50, T3: T1 + Bio-silica, T4: T1 + Biochar SP-50 + Bio-silica, T5: T1 + Volkanorf K-424. To study the farmer's land management system, discussions were held with farmer groups at the research location. The dosage of fertilization and soil ameliorant in each treatment is presented in Table 3.

| Treatment | Ponska kg ha\(^{-1}\) | Urea t ha\(^{-1}\) | SP-36 | Biochar SP-50 | Volkanorf K-424 l ha\(^{-1}\) | Compost | Bio-silica |
|-----------|------------------------|----------------|-------|----------------|---------------------------|---------|-----------|
| TP        | 0.7                    | -              | -     | -              | -                         | -       | -         |
| T1        | 266.7                  | 33.3           | -     | -              | -                         | -       | -         |
| T2        | 266.7                  | 33.3           | 5     | -              | -                         | -       | -         |
| T3        | 266.7                  | 33.3           | -     | -              | -                         | -       | 4         |
| T4        | 266.7                  | 33.3           | 5     | -              | -                         | -       | 4         |
| T5        | 266.7                  | 33.3           | -     | 5              | -                         | -       | -         |

Table 3. Dosage of fertilization and soil ameliorant in each treatment.
The dosage of Phonska fertilizer (NPK 15-15-15) in the farmer’s treatment was similar as the recommended fertilizer dosage, which was 400 kg ha\(^{-1}\). Farmers used urea almost twice as high as the recommended dosage. In the balanced fertilization treatment, there was an additional SP-36 fertilizer. Phonska and urea in TP treatment were given twice, namely at 7 and 45 days after planting 50% respectively. T1-T5 was also given twice at 7 and 45 days after planting with a proportion of 45 and 55%, while SP-36 was given at the time of planting. Biochar SP-36 and Vulkanford K-424 were given when planting in rows in the planting path, compost in the farmer's treatment was also given when planting right in the plant hole. Bio-silica was given twice, namely 50% (2 liters) at 30 days after planting, the rest was given at 50 days after planting. Two liters of Bio-silica were dissolved in water to obtain a solution of 200 liters, then sprayed over the soil surface. Corn was planted at a spacing of 75 cm x 20 cm in experimental plots (each with an area of 22.5 m\(^2\)) on 26 May 2018.

Parameters observed were: (1) soil physical properties, namely bulk density measured using the gravimetric method, total pore space (determined based on bulk density and particle density), proportion of pore space (determined based on pF measurement results, measured using pressure plate apparatus), as well as water soluble aggregate determined by wet and dry sieving methods. Sampling of soil samples to measure soil physical properties was carried out using a ring sample the day before corn harvest; (2). Soil chemical properties, namely organic C and N, were analyzed using the CN analyzer, the pH of H\(_2\)O and KCl extract, bases can be exchanged was determined by extracting NH\(_4\) Acetate 1 N at pH 7. Composite soil samples for analysis of soil chemical properties were taken on each experimental plot one day before corn harvest; (3) Plant parameters observed were plant growth (plant height at 2, 4, 6, 8, and 10 weeks after planting and crop production (dry weight of biomass, cob and seeds). Data on the observed soil and plant characteristics were statistically analyzed using analysis of variance (ANOVA) or diversity testing with a confidence interval. To analyze the differences between treatments, the LSD test was used at a significant level of 5%.

3. Results and discussion

3.1. Effect of treatment on soil physical properties

Figure 2 showed the effects of the treatment on bulk density (BD), total pore space, and pore distribution. The highest BD values (0.91 g cm\(^{-3}\)) and the lowest (0.80 g cm\(^{-3}\)) were shown by the treatment of TP (farmer management) and T4 (Biochar SP-50 + Bio-silica), respectively. Biochar SP-50 (T2) produced the second lowest BD with 0.88 g cm\(^{-3}\). Soil with lower BD indicates better soil physical condition. The lowest BD on T4 treatment was not followed by the highest total pore. The highest total pore was achieved by TP treatment. To study the physical properties of soil that is conducive to plant growth, Sudirman et al. [41] stated that knowledge about soil pore size distribution (which can be obtained from water retention or pF measurements) is more useful than total pore only. Based on the results of water retention measurements, the highest water content at pF 4.2 (at the point of permanent wilting) was achieved by the TP treatment (Table 4). This indicates that the pores in the TP treatment were dominated by micro pores, which were difficult for plants to absorb. Meanwhile, T4 treatment had water content at pF4 which was significantly lower than that without soil ameliorant (TP and T1). This data also shows that in the TP treatment, the plant will be at a permanent wilting point if the moisture content is <32% by volume, while in T4 treatment, the permanent wilt point will occur at a moisture content <25% by volume.

Based on the pore distribution, T4 treatment also had better physical properties than other treatments (Figure 2). The highest aeration pore (fast drainage pore) was achieved by T4 treatment (Figure 2), which was 16% by volume or classified as high category, while in other treatments it ranged from 11-14% or was in the medium based on [41]. The slow drainage pore category in all treatments was low. Available water pores in T4 and T3 treatments were about 11% by volume or classified as moderate, while in other treatments it ranged from 9-10% by volume or classified as low.
The positive effect of biochar on improving physical properties is also shown by the results of previous studies of acid upland with sandy texture [14, 22, 42], on Alfisols and Andisols soils [9]. Canqui [43] based on a literature study also shows the positive effect of biochar on BD, porosity, and aggregate soil stability. However, to get a significant effect, the dose used was still relatively high of >5 t ha\(^{-1}\).

**Figure 2.** Effect of treatment on bulk density (a), total pore, aeration pore, slow drainage pore, and water available pore (b).

**Table 4.** Effect of treatment on water retention.

| Treatment | Water content (%) at pF 1 | pF 2 | pF 2.54 | pF 4.2 |
|-----------|--------------------------|------|---------|--------|
| TP        | 51.98a                   | 46.39a | 40.98a  | 31.55a |
| T1        | 50.82a                   | 44.35a | 38.65a  | 29.29a |
| T2        | 50.16a                   | 43.72a | 39.06a  | 28.86ab|
| T3        | 49.59a                   | 44.55a | 40.07a  | 28.98ab|
| T4        | 47.49a                   | 40.74a | 35.92a  | 25.39b |
| T5        | 50.63a                   | 43.51a | 37.73a  | 28.63ab|

*Number in the same column followed by the same letter are not significantly different at alpha 5% based on the BNJ test.

Soil ameliorant treatment also has a positive effect on water aggregate stability/WAS (Figure 3). The average WAS value in the T2, T2, T4, and T5 treatments was more than 80%, while in the treatment without soil ameliorant (TP and T1) the average was around 80%. The highest WAS value (90%) was also achieved by T4 treatment (a combination of biochar and bio-silica). This means that the addition of bio-nano-silica can increase the effectiveness of Biochar SP-50 in improving soil physical properties. Based on the results of the literature study [44] the reasons for stimulation of soil aggregation can be attributed to biochar surface characteristics, which result in direct binding of soil particles or firstly sorption of soil organic matter, which then binds soil particles. This behavior causes occlusion of biochar into aggregates. The other possibility is the carbon contained in biochar can act like glue and act as a cementing agent [45]. Meanwhile, the Si contained in Bio-silica can act as inorganic binding agents in the soil aggregation process. As stated by Mahesh et al. [46] that some cations (Si\(^{4+}\), Fe\(^{3+}\), Al\(^{3+}\), and Ca\(^{2+}\)) induce the precipitation of selected compounds such as, hydroxides, phosphates and carbonates, promoting the aggregation of primary particles.
3.2. Effect of treatment on soil chemical properties
The data in Table 5 shows the effect of the treatment on soil chemical properties consisting of pH, organic C and N content, CN ratio, potential content of K and P, and available K. Balanced fertilization treatment and soil ameliorant significantly affected soil organic C content. The treatment applied in this study had no significant effect on soil pH. Previous research results showed that although the average biochar has a relatively high pH [17], on non-acid soils, biochar has no significant effect on soil pH [47]. Whereas upland with acid soil, biochar showed a significant effect on increasing soil pH [13, 47], which is very necessary to overcome the main limiting factor in agricultural development in this agro-ecosystem. The treatment applied also had no significant effect on soil N content, even though Biochar SP-50 had a relatively high N content compared to other soil ameliorants tested. Based on a literature study conducted by Nurida [17] showed that there are variations in the effect of biochar on soil N content. In soils with poor conditions, biochar application did not significantly affect soil N content.

Organic C content in T4 treatment was significantly higher than other treatments, except with T2 treatment, which was the same using Biochar SP-50. The results of a literature study by Nurida [17] showed an inconsistent effect of biochar on soil organic C content, namely that there is no effect, increase, or vice versa. A decrease in soil organic C content may occur if the loss of C for example due to erosion is still higher than that applied. Volkanorf which is a mixture of volcanic ash and compost actually also contains C-organic which is higher than Biochar SP-50. However, Volkanorf has no significant effect on soil organic C. This can be due to the organic C contained in Volkanorf, organisms that were easy to decompose. Another case with C contained in biochar which is more stable, Winsley [48] states that biochar is very stable and long-term form of carbon sequestration overall, because of its inert nature and resistance to biochemical damage.

The treatment of balanced fertilizers and soil ameliorant also had a significant effect on the potential K₂O content (25% HCl extract), the highest value was achieved in T2 and T4 treatments, namely the Biochar SP-50 and Biochar SP-50 + Bio-silica, the lowest content was in the T3 treatment (Bio-silica). The average content of potential P₂O₅ (25% HCl extract) and available K₂O (Morgan extract) in the Biochar SP-50 treatment with or without Bio-Silica were also relatively higher than other treatments.
Table 5. Effect of treatment on pH, organic C and N, CN, potential K and P, available K.

| Treatment | Ph   | Org-C | Org-N | CN Ratio | K<sub>2</sub>O (HCl 25%) | P<sub>2</sub>O<sub>5</sub> (HCl 25%) | K<sub>2</sub>O Morgan |
|-----------|------|-------|-------|----------|--------------------------|---------------------------------|----------------------|
|           | H<sub>2</sub>O | KCl   | ------ % ------ | ------mg100g<sup>-1</sup> ------ | ppm                    |                                 |                      |
| TP        | 7.38a<sup>*)</sup> | 6.34a | 1.07c | 0.05a | 0.05a | 35.95ab | 9.04a | 176.60a |
| T1        | 7.41a | 6.26a | 1.19bc | 0.06a | 0.06a | 29.59ab | 7.49a | 135.39a |
| T2        | 7.41a | 6.27a | 1.28ab | 0.07a | 0.07a | 39.06a | 9.12a | 171.85a |
| T3        | 7.59a | 6.42a | 1.12bc | 0.05a | 0.05a | 28.41b | 6.68a | 123.00a |
| T4        | 7.48a | 6.34a | 1.32a | 0.06a | 0.06a | 43.03a | 11.00a | 214.53a |
| T5        | 7.61a | 6.45a | 1.19bc | 0.05a | 0.05a | 37.65ab | 8.41a | 158.95a |

<sup>*)</sup> Number in the same column followed by the same letter are not significantly different at alfa 5% based on the BNJ test.

3.3. Effect of treatment on plant growth and production

Improvements in soil quality as a result of the treatment are expected to have a positive impact on plant growth and crop production. The results of this study showed that the treatment applied had a significant effect on growth of maize (Table 6). Plant height in T2 treatment (Biochar-SP50) was significantly higher than the other treatments. Enrichment Biochar SP-50 with Bio-silica did not significantly affect plant growth, as indicated by plant height which was not significantly different from other treatments.

Table 6. Effect of treatment on growth of maize plants.

| Treatment | Plant height (cm) at age (weeks after planting) |
|-----------|-----------------------------------------------|
|           | 2 | 4 | 6 | 8 | 10 |
| TP        | 19.66c<sup>*)</sup> | 45.9bc | 88.5bc | 196.20b | 219.83b |
| T1        | 20.2ab | 41.8ab | 102.4ab | 202.18ab | 224.20ab |
| T2        | 21.4a | 44.8a | 128.8a | 213.90a | 232.98a |
| T3        | 19.3c | 43.7c | 112.1c | 194.53b | 223.30ab |
| T4        | 20.5ab | 47.2ab | 104.0ab | 205.13ab | 228.85ab |
| T5        | 20.2b | 42.0b | 111.9b | 201.60ab | 229.55ab |

<sup>*)</sup> Number in the same column followed by the same letter are not significantly different at alfa 5% based on the BNJ test.

Although it had a significant effect on plant growth, the applied treatment could not significantly increase the yield of maize, as indicated by the production of wet and dry biomass, wet cobs production, and dry shells, which were not significantly different between treatments (Table 7). This is most likely because of the inability of the treatment applied to overcome drought stress. Figure 1 shows the rainfall conditions during the growth and production period of maize. The dry season occurs from June to October 2018 and the generative period of corn plants occurs at the peak of the dry season, which is around August-September 2018. The impact of biochar on plant productivity depending on the characteristics of biochar properties, dosage used and its ability to cope the main constraint of the land to which biochar is applied [17]. A published study showed the positive effect of the use of biochar on plant productivity in dry land in NTB, but accompanied by the application of vertical mulch to cope with drought stress [5].
Table 7. Effect of treatment on maize production.

| Treatment | Yields (t ha⁻¹) | Wet biomass | Dry biomass | Wet cob | Dry shells |
|-----------|----------------|-------------|-------------|---------|------------|
| TP        |                |             |             |         |            |
| T1        | 16.8a*        | 6.6a        |             | 12.6a   | 7.1a       |
| T2        | 16.4a         | 6.5a        |             | 13.2a   | 8.3a       |
| T3        | 16.7a         | 6.9a        |             | 13.1a   | 7.7a       |
| T4        | 16.5a         | 6.6a        |             | 13.0a   | 7.3a       |
| T5        | 16.8a         | 6.9a        |             | 12.7a   | 7.3a       |

*Number in the same column followed by the same letter are not significantly different at α = 5% based on the BNJ test.

4. Conclusions

Soil ameliorants treatment (Biochar SP-50, Biosilica, and Volkanorf) had a positive effect on water aggregate stability. Treatment of Biochar SP-50 in combination with Bio-silica had a positive effect on other several parameters of soil physical properties (BD, aeration pore, and water availability pore). Balance fertilization accompanied by biochar SP-50 application without and with bio- silica gave a positive effect on the content of soil organic C and K-potential. Balanced fertilization and soil ameliorant also significantly affected corn growth. Plant growth in balanced fertilization + biochar SP-50 was significantly higher than other treatments, while corn production between treatments did not show a significant difference. The treatment applied seems insufficient to overcome the limiting factor of water availability that it was unable to support a significant increase in crop production.

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