Water use efficiency and yield of shallot on coastal sandy soil ameliorated by clay and biopolymer

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Abstract. Low water holding capacity and too high permeability are the main problems of coastal sandy soil. The main objective of the research was to improve water use efficiency and yield of shallot on coastal sandy soil. The experiment was arranged in a split-plot design. The main plot was three levels of watering, consisting of 9, 6, and 3 mm daily, and the sub-plot was the ameliorant types, consisting of clay soil (Vertisol or Inceptisol) combined with biopolymers (tapioca and polyvinylalcohol/PVA). The combination consisted of Vertisol + 1\% tapioca, Vertisol + 0.1\% PVA, Inceptisol + 1\% tapioca, and Inceptisol + 0.2\% PVA. Control treatment, untreated coastal sandy soil with 9 mm daily of watering, was made for comparison. The result showed that the clay soil + PVA as an ameliorant significantly increased the number of leaves and tillers compared to other ameliorants and control. The use of Vertisol + 0.1\% PVA increased the fresh and dry weight of bulbs by 13.7 and 13.4\% compared to the control. Its combination with the watering of 3 mm reached the water use efficiency of 7.3 kg.m\textsuperscript{-3} and saved 51.3\% compared to the control. The combination of clay and PVA is recommended for coastal sandy soil because it is able to improve the water use efficiency and yield of shallots.

1. Introduction
The land-use competition for agriculture, housing, and industry prompts the conversion of productive agricultural land to non-agricultural areas, resulting in decreasing agricultural land. This phenomenon happens in most agricultural centers in Indonesia, which encourages the use of marginal land for agriculture. The potential coastal land in the Special Region of Yogyakarta stretches from Bantul to Kulon Progo along ± 131 km \cite{1}. In the last 20 years, the cultivation of horticultural crops such as chili peppers and shallots is starting to utilize coastal sand fields along the South Coast of Yogyakarta.

Similar to other marginal lands in general, coastal sandy soil has restrictions in physical and chemical properties, as well as in micro climate characteristics. Sandy soil is characterized by a sand fraction> 90\%, affecting the physical and chemical properties of the soil. Low water binding ability and very fast water escape from the soil are the impact of the dominance of sand fraction and single grained structure \cite{2, 3}, and also the general problem in coastal sandy land is low fertility due to low organic matter content and low cation exchange capacity \cite{4, 5}.

The application of soil ameliorant in the form of clay or manure has been carried out by local farmers in the last 10 years. The cation exchange capacity, water holding capacity and stability of sandy soil aggregate increased after amendment using clay soil \cite{6, 7, 8}. Moisture retention in sandy
soils increases after amelioration using clay [9, 10]. However, in coastal sandy land, the addition of clay soil is not optimal for increasing soil moisture retention (low water efficiency) as evidenced by the high volume of watering in shallots cultivation, which ranges from 9-15 mm day\(^{-1}\).

The water holding capacity of coastal sandy soil potentially increases after application of polymeric because polymeric materials attaches soil particles and increase moisture retention [11, 12, 13]. Polysaccharides and humic acid are examples of natural polymers, while synthetic polymers are from water-soluble polymers, for example, polyvinylalcohol and polyacrylamide [11, 13]. Polymers attach sand and clay particles so that the soil is able to hold moisture longer [14, 15]. Amendment using 0.1% PVA significantly increases the aggregate stability of the soil [16]. The advantage of soil ameliorant polymers derived from organic materials is to improve the physical and chemical properties of the soil. Nevertheless, their characteristic of being easily decomposed causes the polymers to be applied in large quantities at certain times. Indonesia's tropical climate provides a comfortable environment for decomposer microbes to decompose so that the residual effects of organic matter can be no longer than 30 days. The residual effects of organic matter application on nutrient availability will decrease after 20 days [17].

The use of vertisol clay, zeolite, and river mud as ameliorant material increases the available moisture content of coastal sandy soil [18, 19]. However, there are still little data comparing the effect of clay types combined with natural and synthetic polymers on moisture retention. The properties of polymers that can be adhesive to sand-clay particles are thought to be able to maintain moisture and increase the efficiency of water use in coastal sandy land. The study aimed to determine the volume of water and the best type of ameliorant to increase the efficiency of water use and the yield of shallots in coastal sandy land.

2. Materials and Method

2.1. Soil amelioration of using clay and polymer materials in sandy coastal land
The research was conducted from June to August in coastal sandy land (98% sand, 1% silt, 1% clay), located 49 km in the South Coast of Yogyakarta, Indonesia. The experiment was arranged in a split-plot design, consisting of three replications. The main plot was the level of watering, comprising three levels, namely 9, 6, and 3 mm daily. The sub-plot was the combination of ameliorant types, consisting of 4 combination types, namely Vertisol+1% tapioca, Vertisol+0.1% PVA, Inceptisol+0.2% PVA, and Inceptisol+1% tapioca.

The size of each plot was 3 m\(^2\) with a sand weight of 990 kg per plot (height = 20 cm, bulk density = 1.65 g cm\(^{-3}\)). The amount of ameliorant was determined based on the percentage of the weight of sand. Vertisol (60% clay) and Inceptisol (39% clay) were 83 kg and 127 kg, respectively, per plot equal to 5% clay from the weight of the coastal sandy soil. Biopolymers consisting of 1% tapioca, 0.1% PVA and 0.2% PVA (weight/weight) were prepared using 9.9 kg tapioca, 0.99 kg and 1.98 kg PVA dissolved in 20 liters of hot water at 90°C for tapioca and 60°C for PVA. The application was carried out by evenly mixing the clay and biopolymers in each plot and incubating the mixture for two weeks.

Analysis of the physical properties of coastal sandy soil after amelioration included texture by the hydrometer method [20], moisture content at pF 2.54 and 4.2 using the pressure plate apparatus method, bulk density using the ring sample method and permeability using the constant head method [21].

2.2. Shallots planting
The shallots were planted on plots with a distance between plots of 0.5 m and a distance between blocks of 1 m wide. The seeds of shallot cultivar 'Tiron' were sowed at a spacing of 15 cm x 15 cm in rows. Basic fertilizers were manure 6 kg plot\(^{-1}\), urea, SP-36 and KCl each of 45 g plot\(^{-1}\), and ZA 75 g plot\(^{-1}\).
Watering was given in the same level (9 mm) until 15 days after planting (dap). Starting from 16 dap, the watering treatments were applied up to 5 days before harvest. Watering was given in the morning and evening, each half of the volume of the tested treatment. The observations of vegetative growth were made on the plant height, the number of leaves and the number of tillers counted once a week on three representative plants. Proline level analysis of plants [22] was carried out at 35 dap, and harvesting was carried out at 72 dap when 75-85% of leaves began to dry out, the stems began to wither, and the bulbs emerged on the ground surface. Water use efficiency was calculated by the following formula [23]:

\[
\text{Water use efficiency} = \frac{\text{Weight of shallot bulbs (kg)}}{\text{Total water used (m}^3)}
\]

2.3. Data analysis
The data was analyzed with Analysis of Variance (ANOVA) followed by Duncan’s Multiple Range Test at a confidence level of 95%. The analysis was performed using SAS software version 9.3.

3. Results and Discussion

3.1. Texture, bulk density, and permeability of coastal sandy soil
The dominance of sand fraction causes water to drain quickly so that the soil is unable to retain soil moisture [2]. The bulk density of 1.65 g cm\(^{-3}\) (Table 1) strengthens that the soil is not structured, with low aggregation and pore volume making it difficult to retain moisture.

| Variable                   | Value   |
|----------------------------|---------|
| Bulk density (g cm\(^{-3}\)) | 1.65    |
| Moisture content at pf 2.54 (%) | 4.04    |
| Moisture content at pf 4.2 (%)  | 1.72    |
| Available soil moisture (%)   | 2.32    |
| Permeability (cm hr\(^{-1}\))  | 73.9    |

Low moisture retention can be seen from the moisture content, at field capacity, reaching only 4.04%. In addition, available water of 2.32% indicates that very little water can be held by sandy soil. Low moisture content shows the inability of the sand to retain moisture because the macropores containing air are more dominant than the micropores of the retaining moisture.

3.2. Plant growth
The types of ameliorant have a single effect on the number of leaves and tillers. Meanwhile, watering volumes did not give any significant effect (Table 2).

The treatment combination of clay-PVA produced a higher number of leaves than the combination with clay-tapioca. A similar effect was also observed in the number of tillers. The decomposition of tapioca will reduce the ability to attach particles so that nutrients are easier to leach, affecting the number of leaves and tillers formed. The average temperature at the research site reached 34\(^{\circ}\)C, stimulating the decomposition of natural polymers such as tapioca which reduces its function as an adherent to soil particles. The decomposition activity increase in high temperatures [2]. Besides, sandy soils are very low in clay-organic matter bonds. These bonds serve as physical protection of clay against organic matter from decomposer microbial activities [2, 24].

The properties of synthetic polymer is slowly decomposed, PVA inhibit organic C mineralization even though these effects will gradually decrease [13]. This explains that the effect of particle attachment by PVA lasts longer than by natural polymers, affecting the decrease in nutrient leaching.
The decreasing of nutrient leaching such as N will increase its availability in coastal sandy soil. The availability of nutrients such as N, Ca and P, which plays a role in plant growth and cell division [25], according to the growth phase affects the number of leaves and tillers formed.

### Table 2. Effects of the level of watering and ameliorant type on the number of leaves and tillers at maximum vegetative phase

| Watering level (mm) | Vertisol + 1% Tapioca | Vertisol + 0.1% PVA | Inceptisol +0.2% PVA | Inceptisol +1% Tapioca | Mean   |
|---------------------|-----------------------|---------------------|----------------------|------------------------|--------|
| Number of leaves    | 9                     | 29.56               | 37.89                | 42.78                  | 27.11  | 34.33 a |
|                     | 6                     | 27.78               | 38.89                | 40.00                  | 35.33  | 34.25 a |
|                     | 3                     | 34.56               | 38.89                | 36.11                  | 27.11  | 34.17 a |
| Mean                | 28.96 n               | 38.55 m             | 39.63 m              | 29.85 n                | (-)    |
| Mean of treatment   | 34.25 ^a              |                     |                      |                        |        |
| Control             | 35.78 ^a              |                     |                      |                        |        |
| Number of tillers   | 9                     | 4.44                | 6.22                 | 6.11                   | 4.56   | 5.33 a  |
|                     | 6                     | 4.56                | 6.33                 | 5.89                   | 5.00   | 5.44 a  |
|                     | 3                     | 5.44                | 6.33                 | 6.33                   | 3.33   | 5.36 a  |
| Mean                | 4.82 mn               | 6.30 m              | 6.11 m               | 4.29 n                 | (-)    |
| Mean of treatment   | 5.38 ^a               |                     |                      |                        |        |
| Control             | 4.33 ^a               |                     |                      |                        |        |

Remarks: (-) shows there is no interaction effect; means followed the same letters are not significantly different according to Duncan’s Multiple Range Test at 5%; means followed by the same superscript letters are not significantly different according to orthogonal contrast test at 5%.

### 3.3. Proline content and moisture content

Some treatments showed an increase in proline content in leaf tissue, and the highest proline content was observed in the treatment of Inceptisol + PVA 0.2% with a watering of 3 mm (Figure 1). An increase in proline content is a form of osmotic pressure regulation in response to drought stress [23, 26, 27] which indicates that there has been water stress so that more proline is formed. The increase in proline content was relatively small, which ranges from 1 to 16 times compared to plants treated with watering of 9 mm daily. The proline content under environmental stress might be different between plant and can increase up to 100 times compared to optimal conditions [28]. Nevertheless, an extremely damage to plants indicated by high proline content [29].
**Figure 1.** Effects of the level of watering and ameliorant type on the moisture and proline content at maximum vegetative phase

Control treatment, representing practices by local farmers, showed high content of proline. Drought stress experienced by plants under control treatment shows the inability of coastal sandy soils to retain moisture even though the volume of water supplied is quite high. The addition of manure to the coastal sandy soils was not strong enough to resist vertical water flow so that the control experienced faster water loss compared to the sand given ameliorant.

### 3.4. Crop yields
The watering level and ameliorant type, separately, show an effect on total biomass and bulbs (Table 3-4). The highest fresh and dry weight of total biomass and bulbs was observed in the treatment of Vertisol + PVA 0.1%.

**Table 3.** Effects of the level of watering and ameliorant type on the totally fresh and dry weight of shallots (g cluster -1)

| Watering level (mm) | Ameliorant type | Mean |
|---------------------|-----------------|------|
|                     | Vertisol + 1% Tapioca |      |
|                     | Vertisol +0.1% PVA |      |
|                     | Inceptisol+0.2% PVA |      |
|                     | Inceptisol +1% Tapioca |      |
| Total fresh weight  | 49.54 n          | 57.72 n | 51.81 n | (-) |
| 9                   | 58.63            | 69.33  | 53.23   | 48.50  | 57.42 a |
| 6                   | 45.27            | 80.07  | 61.97   | 47.70  | 58.75 a |
| 3                   | 44.73            | 67.43  | 57.97   | 59.23  | 57.34 a |
| Mean                | 31.67 o          | 51.02 m | 40.47 n | 30.31 o | 38.37 x |
| Control             | 58.07 x          | 57.84 x |

Remarks: (-) shows there is no interaction effect; means followed the same letters are not significantly different according to Duncan’s Multiple Range Test at 5%; means followed by the same superscript letters are not significantly different according to orthogonal contrast test at 5%.

Vertisol is dominated by clay minerals that have the ability to expand and absorb water in interlayer space [30]. It becomes a kind of water storage and, when plants need water, will be released slowly [10]. The combination of Vertisol and PVA is able to suppress the leaching of water and nutrients and increase the ability of soil to retain water.

Shallow groundwater in the research site and the dominance of fine sand fraction causes a capillary upward movement of water so that watering volume of 3 mm daily is sufficient for plants. The capillary upward movement of water in the soil with shallow groundwater plays an important role in retaining moisture in the root area [31]. The watering method carried out twice a day, morning and evening, prevents drastic water loss through evaporation during the day, and the water supplied in the evening can be used as a reserve to maintain soil moisture. Beside that, the transpiration reduced as impact from the ability of plants to control the opening of the stomata [25].
Table 4. Effects of the level of watering and ameliorant type on the fresh and dry weight of shallot bulbs (t ha\(^{-1}\))

| Watering level (mm) | Vertisol + 1% Tapioca | Vertisol + 0.1% PVA | Inceptisol + 0.2% PVA | Inceptisol + 1% Tapioca | Mean |
|---------------------|------------------------|----------------------|------------------------|------------------------|------|
| Fresh weight of bulbs |                        |                      |                        |                        |      |
| 9                   | 16.50                  | 23.17                | 17.93                  | 13.00                  | 17.65 a |
| 6                   | 12.43                  | 26.83                | 19.90                  | 13.72                  | 18.22 a |
| 3                   | 13.87                  | 20.83                | 20.15                  | 13.17                  | 17.00 a |
| Mean                | 14.27 o                | 23.61 m              | 19.33 n                | 13.29 o                | (-)  |
| Mean of treatment   |                        |                      |                        |                        | 17.63 x |
| Control             |                        |                      |                        |                        | 20.77 x |
| Dry weight of bulbs |                        |                      |                        |                        |      |
| 9                   | 15.17                  | 21.43                | 16.67                  | 11.70                  | 16.24 a |
| 6                   | 10.77                  | 24.83                | 16.47                  | 12.27                  | 16.08 a |
| 3                   | 11.83                  | 19.40                | 18.73                  | 12.10                  | 15.52 a |
| Mean                | 12.59 o                | 21.89 m              | 17.29 n                | 12.02 o                | (-)  |
| Mean of treatment   |                        |                      |                        |                        | 15.95 x |
| Control             |                        |                      |                        |                        | 19.33 x |

Remarks: (-) shows there is no interaction effect; means followed the same letters are not significantly different according to Duncan’s Multiple Range Test at 5%; means followed by the same superscript letters are not significantly different according to orthogonal contrast test at 5%.

Table 5. Effects of the level of watering and ameliorant type on the number and diameter of shallot bulbs

| Watering level (mm) | Vertisol + 1% Tapioca | Vertisol + 0.1% PVA | Inceptisol + 0.2% PVA | Inceptisol + 1% Tapioca | Mean |
|---------------------|------------------------|----------------------|------------------------|------------------------|------|
| Number of bulbs     |                        |                      |                        |                        |      |
| 9                   | 8.78                   | 14.56                | 13.44                  | 10.78                  | 11.89 a |
| 6                   | 9.11                   | 12.67                | 15.22                  | 15.67                  | 13.17 a |
| 3                   | 12.44                  | 13.22                | 14.56                  | 11.00                  | 12.81 a |
| Mean                | 10.11 n                | 13.48 mn             | 14.41 m                | 12.48 mn               | (-)  |
| Mean of treatment   |                        |                      |                        |                        | 12.62 x |
| Control             |                        |                      |                        |                        | 9.83 x |
| Bulb diameter (cm)  |                        |                      |                        |                        |      |
| 9                   | 1.40                   | 1.81                 | 1.69                   | 1.35                   | 1.56 b |
| 6                   | 1.35                   | 1.80                 | 1.72                   | 1.40                   | 1.57 b |
| 3                   | 1.54                   | 1.69                 | 1.70                   | 1.57                   | 1.63 a |
| Mean                | 1.43 n                 | 1.77 m               | 1.71 m                 | 1.44 n                 | (-)  |
| Mean of treatment   |                        |                      |                        |                        | 1.59 x |
| Control             |                        |                      |                        |                        | 1.76 x |

Remarks: (-) shows there is no interaction effect; means followed the same letters are not significantly different according to Duncan’s Multiple Range Test at 5%; means followed by the same superscript letters are not significantly different according to orthogonal contrast test at 5%.

The watering level did not affect the number of bulbs. However, shallots treated with watering of 9 and 6 mm daily produced smaller bulbs compared to shallots treated with watering of 3 mm daily (Table 5). This result might be related to the nature of shallots, which do not like excessive moisture.
Referring to the research of [32], the dry weight and pyruvate content of shallots at 75% of available moisture is lower than at 50%. The excessive amount of water will increase evapotranspiration in alliaceous plants. Clay + PVA produced larger bulbs than clay + tapioca, showing the ability of synthetic polymers to suppress water loss due to leaching and evaporation [33].

3.5. Water use efficiency
The level of watering of 3 mm daily combined with Vertisol + 0.1% PVA and Inceptisol + 0.2% PVA reached the highest water use efficiency of 7.3 and 7.1 kg m$^{-3}$, respectively (Figure 2). High efficiency shows that less water is used by plants to produce 1 kg of bulbs.

![Figure 2. Effects of level of watering and ameliorant type on the water use efficiency](image)

The figure above showed that water is used efficiently in soils ameliorated using Vertisol + 0.1% PVA and Inceptisol + 0.2% PVA that watering 3 mm daily. Water was saved by 51.3% compared to the highest watering volume (Table 6).

| Watering level | Amount of water used (m$^3$ha$^{-1}$) | 1-15 days after planting | 16-65 days after planting | Total |
|----------------|--------------------------------------|-------------------------|-------------------------|-------|
| 9 mm daily     | 1350                                 | 4500                    | 5850                    |
| 6 mm daily     | 1350                                 | 3000                    | 4350                    |
| 3 mm daily     | 1350                                 | 1500                    | 2850                    |

1 mm equals to 0.001 m$^3$ water per m$^2$ of land

The clay increases the ability of coastal sandy soils to hold moisture and nutrients [9, 34] through increasing CEC and soil buffering that will suppress leaching [35], increase surface area, attach particles, and reduce evaporation [36, 37]. PVA increases the cohesion between particles, increasing the number of macroaggregates [10, 38] and causing the aggregates to be more stable [39], thus, the soils are more able to retain moisture.

4. Conclusion
Single treatment of Vertisol + PVA 0.1% had the best effect on increasing the production and diameter of shallot bulbs. Amelioration increased the fresh and dry weight of bulbs, respectively, by 13.7 and 13.4% compared to the control. Amelioration using Vertisol + PVA 0.1% combined with watering of 3 mm daily reached the highest water use efficiency, which was 7.31 kg m$^{-3}$, and increased by 106% compared to the control. The high efficiency of water use was also achieved in the combination of the
watering of 3 mm daily and Inceptisol + PVA 0.2%, which was 7.07 kg m\(^{-3}\), and increased by 99% compared to the control. Clay and PVA increased the retention of moisture in coastal sandy soil and reduced evaporation so that water can be used efficiently by plants.

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