



Contributions of soil biochemical properties as land productivity determinants for pineapple (*Ananas comosus* [L.] Merr.) plantation in Central Lampung Regency, Indonesia

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Abstract. *One of the management challenges in plantation scale cultivation of pineapple in Indonesia is the still occurrence of production disparities across the cultivated land, although the recommended cropping practices have been implemented for decades. In the case of a pineapple plantation in Central Lampung Regency, contributions of soil biochemical properties, in terms of soil enzyme activities, as determinants of land productivity have never been elaborated. This study aimed to evaluate the relationships between biochemical and other soil properties and land productivity in a pineapple plantation in Indonesia. Rhizosphere-soil composite samples were taken purposively from 4 stations at the largest Indonesian pineapple plantation, representing blocks with high and low yield levels and vegetative and generative growth phases. Relationships amongst the studied parameters were evaluated using PCA and linear multiple regression analysis. The results showed significant contributions of the rhizosphere-soil properties on the pineapple yield according to the best-fit equation: $Yield = 64,895 - 6,546 PCA_1 + 13,057 PCA_2 - 7,722 PCA_4$ ($R^2 = 0,612$), where PCA_1 consisted of soil available-P, available-K, and CEC; PCA_2 was of soil base saturation, total microbe population, activities of soil enzyme cellulase and invertase, and PCA_4 was of soil organic C, silt content, and phosphatase activities.*

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INTRODUCTION

Pineapple is one of the most prospective tropical fruits developed in Indonesian agriculture. Its international demand has been the third highest after bananas and oranges (Zhang *et al.* 2016). This fruit provides many health benefits, such as anti-inflammation, thrombolytic, and fibrinolytic (Ramli *et al.* 2018; Difonzo *et al.* 2019). In addition, Hariyadi *et al.* (2012) reported that the use of pineapple cultivation waste as a substrate for anaerobic fermentation process produced the highest biogas compared to sugarcane bagasse or a combination thereof. Based on the average production data for 2010 – 2014, 74,44% of the Indonesia's pineapple production is supplied from the provinces of Lampung, West Java, North Sumatra, East Java, and

Jambi with contribution of respectively 33,65%, 13,26%, 12%, 8,21%, and 7,33% (Kementerian Pertanian 2015). The largest pineapple producer in Lampung Province is Central Lampung Regency, reaching 99,88%, thus it is also the largest pineapple producer in Indonesia (BPS 2017).

Evaluation of soil fertility status and nutrient cycles, as determining factors of the level and quality of plantation crop production, including pineapple, can be based on the soil microbial activities as reflected by soil enzyme activities in the rhizosphere. Various organic exudates released by the plant roots in rhizosphere are utilized by soil microbes as carbon sources, which then through their enzymatic processes this mechanism favors the provision of nutrients for plants. Root exudation decreases with soil depth. Up to 62% of the soil respiration rate and microbial biomass formation and up to 69% of the organic soil Nitrogen content are occurred and found in the rhizosphere (Natsheh and Mousa 2014).

Long-term application of agrochemicals such as herbicides, pesticides, and inorganic fertilizers in cultivation of pineapple at plantation scale are potentially harmful to the soil environment as it relates xenobiotic compounds to the contamination that will accumulate and leave negatively impacted residues to the soil biological properties (Mansur 2013). Some of these compounds are not easily degraded, so they can be concentrated at low to high level in the living soil biomass. One of the degradation processes of xenobiotic compounds is through alteration in their chemical structure from complex compounds to simpler ones. This process occurs biochemically by involving various soil enzymes. The presence of soil enzymes and their activities is determined by the relationship between soil and environmental factors (Utobo and Tewari 2015). Soil enzyme activity increases with the increasing microbial population or soil respiration. The highest enzyme activity occurs in the rhizosphere because of its highest microbial population and activity (Wallenstein *et al.* 2011). Microbial-C concentration affects positively to the soil enzyme activity (Klose and Tabatabai 1999). The type and activity of soil enzyme is the best indicator of soil microbial activity and at the same time it is a reflection of the level of soil biological fertility. Soil enrichment with various types of organic matter as a microbial energy source will affect soil enzyme's production mechanism and activity (Dhungal *et al.* 2012).

One of the management challenges in plantation-scale cultivation of pineapple in Indonesia is that there is still disparities in the land productivity level across the cultivated area, even though the recommended cultivation practices have been implemented for decades. In the case of a pineapple plantation in Central Lampung Regency the contributions of soil biochemical properties as represented by the activity of various soil enzymes in the rhizosphere as determinant for land productivity level has never been elaborated. This study was aimed to elaborate the relationships between biochemical and other properties of rhizosphere soils and land productivity level expressed as pineapple yield at plantation scale in Indonesia.

MATERIALS AND METHODS

Field Observation Station and Soil Sampling

This research was conducted from January to July 2018. Field observation stations were set up in the plantation area of PT Great Giant Pineapple, Central Lampung Regency, Lampung Province, Indonesia (Figure 1), a tropical dry land dominated by flat landscapes with relatively homogeneous soil characteristics. The ameliorants and fertilizers applied in each cropping cycle (kg ha^{-1}) consisted of Dolomite (2.000), DAP (200), and Kieserite (200) soon after the land preparation, and ZA (50), K_2SO_4 (1.200), and Borax (13) at 60 days after planting (DAT), then Urea (1.125), MgSO_4 (65), FeSO_4 (40), ZnSO_4 (38), CaCl_2 (150), and liquid organic fertilizer (192 L ha^{-1}) applied as foliar fertilizer in every 20 – 30 days.

Rhizosphere-soil composite samples were taken purposively from 4 stations representing cultivated land with low yield ($< 60 \text{ t ha}^{-1}$, designated thereof as L) and high yield ($> 60 \text{ t ha}^{-1}$, designated thereof as H) based on 2017 production data, and plant growth at vegetative phase (7 – 9 months after transplanting, MAT, designated thereof as V) and generative phase (13 - 15 MAT, designated thereof as G). At each station, 5 soil samples were taken as replicates and from each replicate 3 x 100 g composite soil sub-samples were taken and stored in cool boxes prior to analysis. Soil analysis was carried out at the Soil Biotechnology Laboratory and

Soil Chemistry and Fertility Laboratory, Department of Soil Sciences and Land Resource, Faculty of Agriculture, IPB University.

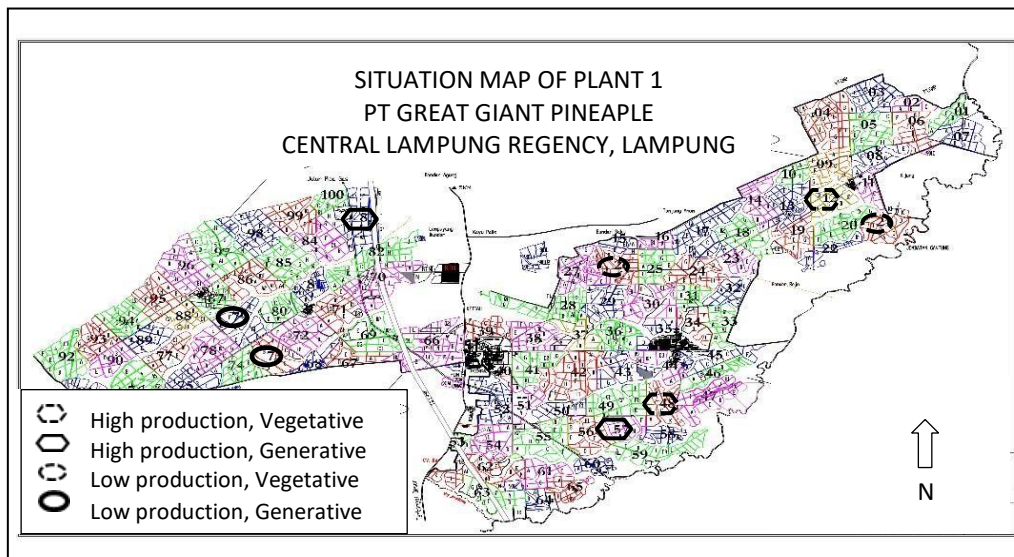


Figure 1 Observation stations and rhizosphere soil sampling locations in a pineapple plantation in Central Lampung Regency, Lampung Province, Indonesia

Characterization of Soil Properties

Soil analysis was carried on 20 samples representing L-V, L-G, H-V, H-G stations, each with 5 replicates. Analysis of soil chemical properties was carried out on pH-H₂O (1:5; pH-meter), organic C (Walkley and Black), total N (Kjeldahl), available P (Bray #1), and available K (Morgan), while of soil physical properties was on soil texture (Pipette) and of soil biological properties was on soil respiration rate (modified Verstraete) and total microbial population (Total Plate Count). Analysis of soil biochemical properties was carried out on the activity of rhizosphere soil enzymes, consisting of urease, cellulase, invertase, and phosphatase.

Urease Activity

The activity of urease was determined according to Unbuffer method (Askin and Kizilkaya 2005). For each soil sample, 2,5 mL 79,9 M Urea substrate was added to the test bottles containing 5 g soil sample, while 2,5 mL distilled water was added to the control bottle. The bottles were closed and incubated at 37 °C. After 2 hours of incubation, 2,5 mL distilled water was added to the test bottles and 2,5 mL 79,9 M Urea substrate was added to the control bottle. Then, 50 mL M KCl were added to each bottle, stirred for 30 minutes, filtered, and 1 mL of the filtrate was pipetted into test tubes and added each with 0,2 mL Nessler's reagent and 9 mL distilled water and homogenized. After 10 minutes, the spectroscopic absorbances were measured at 420 nm wavelength to determine the concentration of NH₄⁺ in mg NH₄⁺ g⁻¹ soil expressing the urease activity.

Cellulase Activity

The activity of cellulase was determined by the method of Hope and Burner (1987). Into centrifuge tubes each containing 1 g soil sample, 0,5 mL carboxy methyl cellulose (CMC) substrate and 5 mL citrate buffer solution was added. The tubes were closed and incubated at 40 °C for 16 hours in a shaking water bath incubator, while the control tube did not undergo the incubation step. The test and control tubes were centrifuged for 10 minutes at 2.500 rpm. Then 1 mL of the filtrate was put into another test tubes, added with 1 mL dinitro salicylic acid (DNS) and 2 mL distilled water, heated in boiling water at 100 °C for 15 minutes. After heating, the tubes were cooled and added each with 10 mL distilled water and shaken homogeneously.

The spectroscopic absorbances were measured at wavelength of 540 nm to determine the concentration of glucose in g glucose g⁻¹ soil expressing the cellulase activity.

Invertase Activity

The activity of invertase in each soil sample was determined using Frankenberger and Dick (1983) method by incubating 5 g soil sample in 15 mL 8% sucrose solution for 24 hours at 37 °C. Then the suspension was reacted with 3,5-dinitrosalicylic acid. The glucose concentration was measured colorimetrically at spectroscopic wavelength of 508 nm in mg glucose g⁻¹ soil expressing the invertase activity.

Phosphatase Activity

The activity of phosphatase was determined by the method of Schinner *et al.* (1996). A test tube containing 1 g soil sample was added with 1 mL 10,6366 mM *p*-nitrophenol-phosphate substrate and 4 mL buffer solution (pH 6,5). The tube was then shaken, closed, incubated at 37 °C for 1 hour and 1 mL 0,5 M CaCl₂ and 4 mL 0,5 M NaOH were added. In the control tube, the addition of the substrate was carried out after the addition of CaCl₂. The tubes were then shaken until the solution was homogeneous and filtered. Then 1 mL of the filtrate was pipetted into another tube, diluted with 9 mL distilled water, and the absorbances were measured using spectrophotometer at wavelength of 400 nm and the concentration of *p*-nitrophenol-phosphate was determined in g *p*-nitrophenol-phosphate g⁻¹ soil expressing the phosphatase activity.

Data analysis

The research data were subjected to Principal Component Analysis (PCA) with the help of XLstat 2019 software to determine the principal components of rhizosphere soil properties that contribute to the pineapple production levels. The results of PCA were presented in the form of a circle graph with quadrants and lines respectively showed the pineapple production and the rhizosphere soil properties. The results of PCA were then evaluated further based on the multiple linear regression analysis to determine the best-fit model or equation that incorporating only significant principal components contributed to the pineapple production.

RESULTS AND DISCUSSION

Results

Soil Chemical and Physical Properties

The rhizosphere soil chemical properties are given in Table 1. Based on the criteria of Balai Penelitian Tanah (2005), the soil reactions of rhizosphere soils amongst the four stations were significantly different at the 1% test level and categorized as acidic (pH-H₂O 4,5 - 5,5, A) to very acidic (pH-H₂O < 4,5, VA). The pH-H₂O of rhizosphere soils at the station of HV (A) > LV (VA) > LG (VA) > HG (VA).

The levels of soil organic C at the four stations were low (1 - 2%), but they were not significantly different amongst the stations. The levels of soil available N as N-NH₄⁺ were significantly different at the 1% test level amongst the stations with the order of N-NH₄⁺ concentration in station HV > HG > LV > LG, while as N-NO₃⁻ it showed similar results but in the opposite order where in station LG > LV > HG > HV. The total soil available N levels expressed as N-NH₄⁺ + N-NO₃⁻ at the four stations were very low (< 1.000 ppm). The levels of soil available P at the four stations were very high (> 15 ppm) and significantly different at the 10% test level amongst the stations with the order of LV > HV > LG > HG. The levels of soil available K amongst the stations were significantly different at the 10% test level, where at station LV > LG > HV > HG. The soil CEC at the four stations was low (5 - 16 cmol (+) kg⁻¹) and significantly different at the 1% test level, with the order at station HV > LV > LG > HG, while the soil base saturation was very low (< 20%) but it was not significantly different amongst the stations.

The result of soil textural analysis (Table 2) shows the dominance of sand fraction (43,5 - 48,75%) compared to clay (28,13 - 36,50%). The rhizosphere soil textural class at stations HV and HG was clay loam, while at stations LV and LG was sandy loam, with unsignificantly different composition of the sand, silt, and clay fractions amongst the stations.

Table 1 Average chemical properties of rhizosphere soils at four observation stations in a pineapple plantation in Central Lampung Regency, Lampung Province, Indonesia

Soil chemical properties	Pineapple production level and plant growth phase				p-value ⁴
	High (> 60 t ha ⁻¹)		Low (< 60 t ha ⁻¹)		
	Vegetative ¹	Generative ²	Vegetative ¹	Generative ²	
pH H ₂ O (1:5)	4,58 ± 0,17a ³	4,08 ± 0,14c	4,46 ± 0,18ab	4,27 ± 0,19bc	0,000***
Organic C (%)	1,05 ± 0,24a	1,29 ± 0,41a	1,08 ± 0,22a	1,10 ± 0,23a	0,495 ^{NS}
N-NH ₄ ⁺ (ppm)	6,44 ± 0,64a	5,76 ± 0,76b	5,13 ± 0,31bc	4,54 ± 0,52c	0,000***
N-NO ₃ ⁻ (ppm)	16,84 ± 0,63d	18,34 ± 0,43c	42,07 ± 0,85b	52,04 ± 0,26a	0,000***
Available P (ppm)	27,57 ± 4,97ab	23,83 ± 2,96ab	40,68 ± 5,51a	23,87 ± 2,69ab	0,092*
Available K (ppm)	5,84 ± 0,94ab	5,4 ± 0,74b	7,07 ± 1,28a	6,11 ± 0,90ab	0,078*
CEC (cmol(+) kg ⁻¹)	13,88 ± 2,75a	10,80 ± 2,22b	12,03 ± 2,65b	11,26 ± 1,52b	0,003***
Base Saturation (%)	8,96 ± 2,28a	6,31 ± 0,89a	7,40 ± 1,67a	8,86 ± 1,78a	0,776 ^{NS}

¹ 7-9 months after transplanting

² 13-15 months after transplanting

³ In the same row, the numbers followed by the same letters are not significantly different according to the DMRT test

⁴ *** Significantly different at the test level of 1%, *10%, ^{NS} Not significant

Table 2 Average content of sand, silt, and clay fraction in rhizosphere soils at four observation stations in a pineapple plantation in Central Lampung Regency, Lampung Province, Indonesia

Soil Texture	Pineapple production level and plant growth phase				p-value ⁴
	High (>60 t Ha ⁻¹)		Low (<60 t Ha ⁻¹)		
	Vegetative ¹	Generative ²	Vegetative ¹	Generative ²	
Sand (%)	43,50 ± 3,02a ³	44,75 ± 6,56a	46,13 ± 14,25a	48,75 ± 7,19a	0,688 ^{NS}
Dust (%)	25,00 ± 6,39a	26,00 ± 6,14a	27,50 ± 5,88a	22,38 ± 4,98a	0,383 ^{NS}
Clay (%)	36,50 ± 7,87a	32,25 ± 4,30a	31,00 ± 8,75a	28,13 ± 9,76a	0,887 ^{NS}
Texture	Clay loam	Clay loam	Sandy clay loam	Sandy clay loam	

1 2 3 4 see description in Table 1

Soil Biological and Biochemical Properties

The characteristics of biological and biochemical properties of the rhizosphere soil are given in Table 3. The total microbial population amongst the stations was significantly different at the 1% test level, with the order at station HG > HV > LG > LV. The activity of cellulase at the four stations was in the order of LV > LG > HV > HG, while for invertase was of HV > HG > LG > LV, and for phosphatase was of HV > LG > HG > LV. Compared to cellulase, invertase, and phosphatase, the urease activity was the highest but it was only significantly different at the 10% test level. The order of enzyme activity amongst the stations for urease was of HG > LG > HV > LV. The rhizosphere soil respiration and microbial-C were not significantly different amongst the stations.

Table 3 Average soil biological and biochemical properties at four observation stations in a pineapple plantation in Central Lampung Regency, Lampung Province, Indonesia

Soil Biological and Biochemical Properties	Pineapple production rate and plant growth phase				p-value ⁴
	High (> 60 t ha ⁻¹)		Low (< 60 t ha ⁻¹)		
	Vegetative ¹	Generative ²	Vegetative ¹	Generative ²	
Total Microbes	(23,4 ± 7,4) x 10 ⁴ ab ³	(29,8 ± 4,9) x 10 ⁴ a	(14,7 ± 6,1) x 10 ⁴ b	(18,7 ± 4,8) x 10 ⁴ b	0,005***
Respiration (mg CO ₂ g ⁻¹)	12,00 ± 5,20a	11,60 ± 5,16a	12,10 ± 4,06a	11,50 ± 4,13a	0,995 ^{NS}
Microbial-C (%)	214,40 ± 81,70a	215,36 ± 110,11a	166,26 ± 85,63a	207,15 ± 157,67a	0,856 ^{NS}
Urease (mg NH ₄ ⁺ g ⁻¹)	4.564,52 ± 1.296,19b	6.097 ± 1.949,85a	3.993,29 ± 625,99b	5.556,25 ± 1.271,03ab	0,061*
Cellulase (g glucose g ⁻¹)	89,84 ± 15,96c	89,34 ± 4,29c	138,37 ± 2,63a	120,62 ± 18,35b	0,000***
Invertase (mg glucose g ⁻¹)	171,12 ± 34,81a	148,01 ± 36,65ab	113,78 ± 15,02b	121,75 ± 13,13b	0,006***
Phosphatase (g p-nitrophenol g ⁻¹)	16,83 ± 6,10a	10,51 ± 2,31bc	8,37 ± 1,69c	14,24 ± 1,93ab	0,002***

^{1 2 3 4} see description in Table 1

Relationships Between Soil Properties and Pineapple Production

The results of PCA (Figure 2) show that there are 6 groups of principal components of soil properties that determine the pineapple production or yield. They are PCA₁ (soil available P, available K, and CEC), PCA₂ (soil base saturation, total microbes, cellulase and invertase activity), PCA₃ (sand and clay fractions), PCA₄ (soil organic-C, silt fraction, and phosphatase activity), PCA₅ (soil pH and urease activity), and PCA₆ (soil respiration and microbial-C). The best-fit multiple linear regression equation that explains the relationship between the pineapple yield and the rhizosphere soil properties with significant contributions involves 3 of the 6 PCA components as follows (equation 1):

$$\text{Pineapple yield} = 64,895 - 6,546 \text{ PCA}_1 + 13,057 \text{ PCA}_2 - 7,722 \text{ PCA}_4 \text{ (R}^2 = 0,612)$$

This equation shows that the soil chemical properties simultaneously and significantly contribute to the pineapple yield of year 2017 in the plantation under studied are base saturation, total microbes, and cellulase and invertase activities with positive effects and organic C, silt fraction, phosphatase activity, base saturation, available P, available K, and CEC with negative effects.

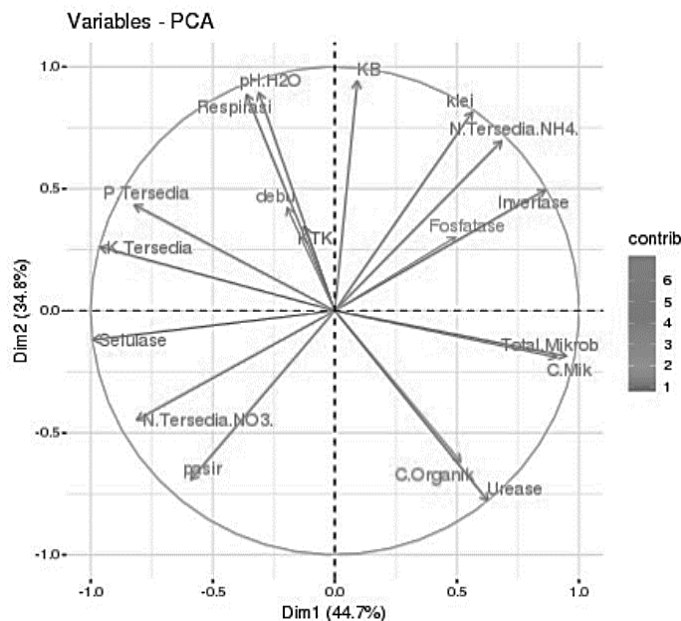


Figure 2 Relationships between rhizosphere soil properties and plantation scale pineapple production in Central Lampung Regency, Lampung Province, Indonesia

Discussion

Rhizosphere Soil Properties

The reaction of the rhizosphere soils at the four stations, which were classified as acidic to very acidic, indicated that the application of 2.000 kg ha⁻¹ of dolomite per cropping cycle could not increase the soil pH to around neutral level. This is also reflected in the soil CEC and base saturation at the four stations that are classified as low and very low. The effect of soil pH on plant growth mainly occurs in the rhizosphere or at the soil depths of 0 - 30 cm (Widiatmaka *et al.* 2015). This is because in this zone plant roots are more concentrated and becomes the center of soil microbial activity.

In acid soils, the solubility and content of polyvalent metals such as aluminum (Al) and iron (Fe) as well as micro-nutrients are relatively high. Besides directly harming the plants, high levels of Al and Fe also increase the soil adsorption of phosphate, thereby reducing the availability and uptake of P for plants. The lowest soil pH value (4,08, very acidic) was measured at the HG station. The lowest soil available P levels were also measured at the HG station, although the levels of soil available P at all the four stations were very high (> 15 ppm). This is related to the DAP fertilization at a dose of 200 kg ha⁻¹ per cropping cycle. This can be related to the activities of soil microbes, especially phosphate solubilizing bacteria (BPF), which have the ability as biological fertilizers by excreting organic acids, including acetic, formic, fumaric, glycolic, glyoxalate, glutamate, lactonic, propionic, citrate, and succinate acids. These acids are able to form chelates with Al and Fe in acid soils so that the phosphate that was formerly adsorbed or fixed by these metals is then released into the soil solution and becomes available to plants (Rao 2008; Boraste *et al.* 2009).

The level of soil N is very influential on the production, organoleptic quality, and sanitation of pineapple fruit. It also maintains plant growth rate that leads to a high production with a shorter growth cycle (Sossa *et al.* 2017). The availability of soil N-NO₃⁻ at stations with high levels of pineapple production was lower than at stations with low production levels and the lowest was measured at station representing low production level and plant vegetative growth phase (LV). As for the availability of soil N-NH₄⁺, the highest was measured at the HV station. This indicates that the uptake or loss of N in pineapple plantations at the vegetative phase was higher in the form of N-NO₃⁻ than N-NH₄⁺. However, with the application of N fertilizer containing only ammonium (NH₄⁺) in the form of Urea and ZA at respectively 1.125 and 50 kg ha⁻¹ per cropping cycle, the levels of soil available N in total or in the form of N-NO₃⁻ + N-NH₄⁺ at the four stations are considered as very low (< 1.000 ppm or 0,1%). The low levels of soil N could be caused by losses through leaching, evaporation, and uptake by plants. Nurmegawati *et al.* (2012) stated that some of the lost N is transported into the harvested plant biomass, some returns to the soil as residual biomass, some is evaporated into the atmosphere and returns to the soil, and some is lost through leaching.

The levels of soil available K in the rhizosphere soils were only significantly different at the 10% test level amongst the stations, with the levels measured at LV > LG > HV > HG stations. Potassium is an essential macro nutrient required by plants, including pineapple, in a very high quantity. Therefore K fertilizer applied in the study area reached 1.200 kg ha⁻¹ K₂SO₄ per cropping cycle. The lowest level of soil available K was measured at HG station which indicated to require higher K intake than at HV, LG, and LV stations. The levels of soil available P and K in the rhizosphere soils can be associated with soil microbial activities. The best-fit production equation obtained shows the contribution of the total soil microbial population variable to the PCA₂ component with positive effect on the level of pineapple production or yield (Figure 2).

Soil dominated by sand fraction will be dominated by macropores and this is inversely proportional to the reactive surface area of the soil solids that reflects the area that can be in contact with water, nutrient ions, energy, or other charged materials. However, pineapple cultivation requires well-drained soil, so that soils characterized by high content of sand fraction as well as organic matter are more suitable for pineapple growth and production (Patricio 2014). The pH of the rhizosphere soils in the study area is in the range of 4,08 - 4,58 with a textural class of clay loam and sandy clay loam. According to Hossain (2016), soil with a clay textural class and sufficient organic matter content with a pH of 4,5 - 6,5 is the best medium for cultivating pineapple.

This range of soil pH values also reflects its significance to the stability of soil microbial activity (Wardy *et al.* 2009), which in turn will affect the activity of rhizosphere soil enzymes.

In the study area, one of the sources of N fertilizer used is Urea. Urea in the soil is enzymatically hydrolyzed by urease to form ammonia and CO₂ along with an increase in soil pH (Adetunji *et al.* 2017). Furthermore, ammonia will be hydrolyzed into ammonium to be able by plants to absorb (Rosmarkum and Yuwono 2002; Winarso 2005). The ammonium can then be nitrified to nitrite and nitrate (Polacco *et al.* 2013). The high or low activity of the urease enzyme depends on the presence of the substrate and the reaction products catalyzed by this enzyme, namely urea and ammonium (Askin and Kizilkaya 2005). The results of this study showed that the activity of urease was the highest compared to cellulase, invertase, and phosphatase, but only significantly different at the 10% test level amongst the stations, with the order of activity at HG > LG > HV > LV stations but had no significant effect simultaneously with other soil properties on the pineapple yield. The highest urease activity observed at the HG station corresponded to the highest soil microbial population that was also measured at the HG station. This means that urease activity in the rhizosphere soil of a pineapple plantation, as the locus for the accumulation of root exudates, increased with the increase in soil microbial population. According to Polacco *et al.* (2013), urease can function to stabilize the rates of different metabolic processes in plant cells under environmental stress conditions.

Soil enrichment with organic matter as an energy source will affect the production mechanism and activity of catabolic enzymes. The activity of rhizosphere soil enzymes that have a significant positive effect simultaneously with other soil properties on pineapple yield at the study area is cellulase and invertase as the components of PCA₂.

Contribution of Rhizosphere Soil Enzyme Activity to Pineapple Production

Based on the production equation obtained, pineapple production in the study area is influenced by the soil properties, including the activities of rhizosphere soil enzymes, namely cellulase, invertase, and phosphatase. Simultaneously with other rhizosphere soil properties, cellulase and invertase activity contributed significantly and positively to the pineapple production as a component of PCA₂, while phosphatase activity contributed significantly but negatively as a component of PCA₄ (Figure 2). These enzymes are produced through the metabolic processes of soil microbes. The functions of microbes in the soil include providing plant nutrients, breaking down organic matter, promoting plant growth, and as biological agents controlling plant pests and diseases (Almeida *et al.* 2015) and this is related to the activities of the resulting soil enzymes. Soil microbes play an important role in the carbon, nitrogen, and sulfur cycles, and in the supply and absorption of nutrients for plants. The metabolism of the three plant macronutrients, namely N, P, and K, all involve soil microbial activities (Fitra *et al.* 2019).

Cellulase is an enzyme synthesized by most microbes including fungi and bacteria during their growth on cellulose substrate to be further enzymatically hydrolyzed into glucose. These microbes can be aerobic, anaerobic, mesophilic, or thermophilic ones. Clostridium, Cellulomonas, Thermomonospora, Trichoderma, and Aspergillus are the main producers of cellulase (Saravanan *et al.* 2013). Cellulase is a high value compound in pineapple cultivation at plantation scale because it helps achieve maximum growth in the recovery process from stressful conditions due environmental factors (Rojas *et al.* 2018). The pH and temperature conditions affect the performance of this enzyme in pineapple cultivation (Ferreira *et al.* 2011). Cellulase can also promote the formation of soil aggregates and soil structure thereby increasing the efficiency of water use by plants (Sarker *et al.* 2018).

Invertase is a polymorphic protein classified as glycoside hydrolase (Mohandesi *et al.* 2016). Invertase enzyme activity also affects pineapple production. This enzyme activity changes considerably with the seasons, the total activity being higher in the dry season (Zhang *et al.* 2016). According to Siddappaji *et al.* (2015), the invertase enzyme group hydrolyzes sucrose into glucose and fructose. Invertase increases during the fruit ripening phase because it plays a role in sugar storage (Taggar *et al.* 2011).

Phosphatase activity is a significant factor that streamlines nutrient uptake under conditions of limited nutrient availability in soil ecosystems. Phosphatase is used to characterize the level of soil P availability (Makoi and Ndakidemi 2008; Adetunji *et al.* 2017). Phosphatase in the rhizosphere soils plays an important role in helping plants absorb nutrients, especially P, because it is able to catalyze the hydrolysis of phosphoric anhydride. Phosphatase activity can originate from plant roots, soil fungi in general, ecto and endo mycorrhizal fungi, or bacteria, which are stimulated by organic materials and organic phosphate compounds (Tarafdar and Marschner 1994). However, in this study, the activity of phosphatase enzyme along with the soil organic C levels and the soil silt content as components of PCA₄ had a negative effect on pineapple production. Further research is needed to elaborate on these specific findings.

CONCLUSION

Soil biochemical properties indicated by the activity of rhizosphere soil enzymes, especially cellulase, invertase, and phosphatase, contributed significantly to the production of plantation-scale pineapple cultivation in tropical dry land. Other soil properties with significant contributions were the levels of available P, available K, total microbial population, organic C, silt content, CEC, and base saturation.

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