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Linking marginal soil to sugarcane productivity in Takalar, Indonesia

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Abstract

Land expansion to meet productivity is often carried out without further consideration or study of the condition of the land. Insufficient soil quality leads to a decline in plant productivity. This research examines the soil conditions on sugar cane plantations in Takalar, Indonesia. We partitioned a single hectare of land into nine distinct observation plots to assess and compare the homogeneity of soil conditions and plant growth within each plot. In this study, we measured the organic carbon and the physical properties of the soil (bulk density and soil permeability), which are the main characteristics that reflect soil conditions in an area. Plant growth parameters such as the number of sugarcane tillers, height, and diameter were measured to compare growth in each plant plot. The research findings indicated that low organic C content values signified a lack of nutrient availability in the soil due to low soil permeability, resulting in a 50% reduction in production. These findings validated the shallow and marginal soil conditions. While soil processing demonstrated a capacity to decrease bulk density at depths of 15–30 cm, it proved ineffective in enhancing soil permeability. Post-tillage, the soil permeability rate at 0–15 and 15–30 cm depths declined, leading to compromised plant growth. Sugarcane plants in Takalar exhibited below-average growth with insufficient plant height (below 200 cm), stem diameter (less than 3 cm), and a low stem count per meter at the initial growth stage. Low organic C content values indicated a lack of nutrient availability in the soil due to low soil permeability, resulting in a 50% reduction in production. This research can be a reference for further research regarding improving soil quality and plant productivity.

1. Introduction

Among many factors, soil quality is the primary determinant of crop productivity. When fertile land cannot meet the required production, agricultural land encroaches on new land previously unsuitable for growing crops (Csikós and Tóth, 2023). One of them is sugarcane cultivation, which is mainly carried out on marginal land to meet the high demand for sugar and ethanol (Awe et al., 2020; Borém et al., 2015; Nabel et al., 2016). On the other hand, the use of marginal land as production land is a big challenge to crop productivity (Csikós and Tóth, 2023; Kang et al., 2013). Marginal land is characterized by low productivity (Kang et al., 2013) and shallow soil depth (Nabel et al., 2016). Limited soil depth can reduce root penetration into the soil, thereby inhibiting the absorption of water and nutrients for plants (Nabel et al., 2016). Sugarcane requires large amounts of water during its growth period to maximize productivity (Wiedenfeld, 2000). If plant roots cannot absorb water optimally, it will affect plant growth, reducing weight, diameter, stem height, and the number of seedlings produced (Misra et al., 2020).

Based on research on land suitability for sugarcane cultivation, deep soil with good drainage is required (Cheavegatti-Gianotto et al., 2011; Jamil et al., 2018a, 2018b). Research has shown that soil properties significantly impact sugarcane productivity (Johnson, 2014). One type of soil that is often found on marginal land is silty clay soil (Wood et al., 2003). Silty clay soil has fine particles, so it is not easy to retain water. It tends to experience compaction, poor drainage, and surface erosion easily (Bonini et al., 2023), making it a type of soil that poses significant challenges. Poor drainage can result in waterlogging in the rainy season and drought in the dry season due to low water reserves in the soil (Misra et al., 2020). Low rainfall can suppress sugarcane growth in marginal land conditions, especially in the germination phase (Kapanigowda et al., 2010). In the rainy season, marginal land cannot hold water due to low permeability, resulting in waterlogging, and in the dry season, there is drought due to low water reserves in the soil (Misra et al., 2020). The water stress that occurs can cause a decrease in yield of up to 70% (Dutta et al., 2018).

Compared with the decline in sugarcane productivity due to water stress due to climate change, fewer studies focus on the soil characteristics of marginal lands that cause the decline in sugarcane productivity. Previous research has revealed increased sugarcane production losses throughout the annual cycle due to water stress due to heavy rain (Le et al., 2021). However, the soil's response to these conditions should have been reported. Other research found higher morphological loss on marginal land when it experienced drought than when it was flooded, such as sugarcane height, which decreased by 18.28% in the dry season and 11.41% in the rainy season (Misra et al., 2020). As far as we know, there are yet to be more in-depth research reports on the relationship of clay soil on marginal land to plant productivity. The relationship between soil characteristics and sugarcane cultivation is complex and often confusing, requiring a different understanding of the difficulties it causes. This research aims to comprehensively examine the challenges of marginal silty clay soil types, exploring how their unique characteristics impact sugarcane growth, development, and yield. This objective can provide a solid basis for further research regarding improving soil quality in sugarcane cultivation on marginal land.

2. Materials and methods

2.1. Study site and observation plot

This research was conducted on a commercial sugarcane plantation in Takalar, South Sulawesi, Indonesia. The research was carried out from the planting season of November 2020 to harvest in October 2021. We divided the 1 ha land into nine observation plots (P1, P2, P3, P4, P5, P6, P7, P8, P9) measuring 30 x 30 m (Figure 1b). Disturbed soil sampling for soil texture analysis was specifically conducted at five observation points (A, B, C, D, and E) (Fig. 1a). The hypothesis underlying this approach was that these observation points could effectively represent the overall soil texture results across observation plots P1-P9. The observation location was chosen because it is an area that represents other locations that have low productivity. This research had no special treatment, such as tillage depth and additional fertilizer doses. All procedures follow the Takalar Sugar Factory Operational Standard processing and planting procedures (Table 1) to determine the leading cause of the decline in sugar cane productivity in Takalar.

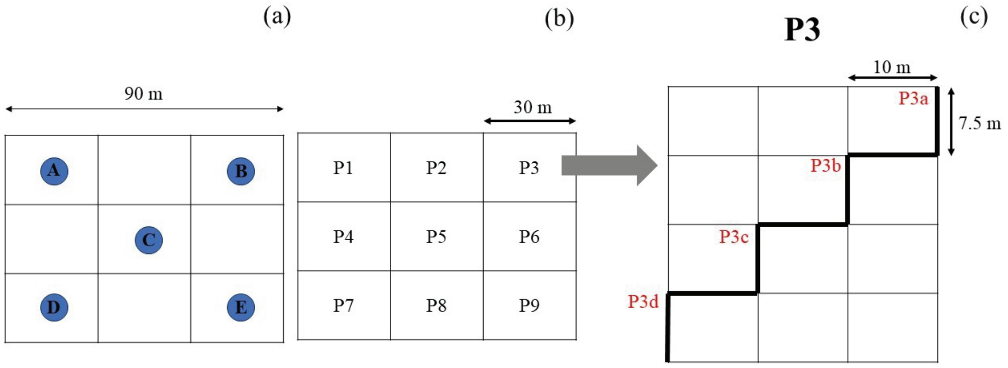

Fig. 1. Observation plot (a) observation plot for soil texture samples (b) observation plot P1-P9 (c) zig-zag method for sugarcane growth measurement

Table 1.
Takalar sugar factory operational standard processing and planting procedures

Kegiatan	Tractor type	Implement	Function	Execution time
Plowing –Plow I –Plow II	150–200 HP	28 inch disk plow	Cutting and turning over the soil	Planting season
Harrow	150–200 HP	Disk harrow	Chop the chunks of soil into finer pieces (crumbs) and chop up the remaining sugarcane and weed stalks	One week after plow II
Furrow	110-150 HP	2 shank furrow	Make a planting hole	One week after harrow
Chissel	120 HP	4 shank chisel plough	Close planting holes	After planting
Cultivation	120 HP	6 shank chisel plough	Loosens the soil so that nutrient absorption is optimal	30 days after planting
Fertilization	120 HP	Fertilizer Applicator (FA)	Fulfills plant nutrient needs	The second fertilization is carried out on mature cane 1.5-2 months
Sub soil interrow	150 HP	2 shank Subsoiler parabolic	Provides deeper and improved root penetration space rooting medium	After the second fertilization, sugarcane aged 2–3 months

2.2. Soil samples collection

Soil samples were taken at two stages, namely pre-tillage and post-tillage. At each stage, we collected intact and disturbed soil samples at 0–15 and 15–30 cm depths in each plot (Fig. 1) in five replications. Undistrubed soil samples were collected using a 5 x 7 cm sample ring. Collecting intact soil samples followed the procedures by Prasadini (2020). The iron plate was placed on the sample ring and then pounded using a hammer until the sample ring enters the ground. Then, the second sample ring was precisely placed on top of the first sample ring and pounded again until half of the second sample ring enters the soil. The soil sample around the ring was then carefully excavated using a crowbar. The surface of the intact soil sample was then gently levelled using a cutter. The samples were used only the results from the first sample ring. The same procedure was carried out at a depth of 15–30 cm. For disturbed soil samples, samples were collected directly by prying the soil and placing it in plastic.

2.3. Soil analysis

Disturbed soil samples were used for measurement the content of soil organic matter, soil texture, and Coefficient of Linear Extensibility (COLE). Organic carbon was measured based on the method proposed by Walkey and Black (1934). Soil texture was determined in the laboratory using the hydrometer method, following USDA guidelines (2017). Soil has elastic properties, namely the ability to expand when wet and shrink when dry, or the Coefficient of Linear Extensibility (COLE) (Yan et al., 2022). The COLE measurement was adapted from the research of Vaught et al. (2006). The dried samples were ground and sieved on a 2 mm mesh sieve. One hundred grams of sample was put into a container, and water was added to form a saturated soil paste. It was then covered and left to equilibrate for 24 hours. Roll the ground pasta into a 60–100 mm stick on a non-stick baking sheet. The next step is to dry the soil in the oven at 105°C for 2.5 hours. The equation determines COLE:

$$\mathrm{COLE} = ((\mathrm{Lm}-\mathrm{Ld}))/\mathrm{Ld} \tag{1}$$

Lm is the moist soil's length, and Ld is the length of the dry stem. COLE has no units.

Undisturbed soil samples were used to measure soil bulk density and permeability. Bulk density is the average density of soil particles and dry soil mass (or weight) per unit volume of soil solids, not including the volume of pores occupied by air or water (McCarty et al., 2015).

$$\text{Bulk density } (\rho b) = (\text{Dry Weight (g)})/(\text{Total Volume of Soil (cm}^3) \tag{2}$$

Soil permeability measurements were adopted based on the constant head method popularized by Klute (1986), which has been applied in previous research by Elhakim (2016) with the formula:

$$K = (Q.L)/(A.t.h) \tag{3}$$

Where K is hydraulic conductivity (cm hours^{-1}); Q is the amount of water flowing per measurement (ml); L is the thickness of the soil sample (cm); A is the cross-sectional area of the soil sample (cm^2); t is measurement time (hours); and h is the height of the water surface from the soil sample (cm).

The test is carried out by soaking intact soil samples until saturated. The principle of measuring the falling head method is based on Darcy's law, namely controlling the sample's water level and calculating the water volume that drips from the intact soil sample within a specific time interval. This measurement was carried out until the water rate is stable and a good enough number of readings were obtained to determine permeability accurately (Elhakim, 2016; Hillel, 1982).

2.4. Sugarcane productivity

Plant productivity measurements were carried out every two months from when the sugar cane is four months old until harvest. The parameters measured were based on previous research by Misra et al. (2020), such as the number of tillers, height, and stem diameter. Measurements were carried out on each plot using the zig-zag method (Figure 1b) based on research references conducted by Wood et al. (2003). Standard operating procedures (SOP) Takalar Sugar Factory is the basis for predicting harvest yields per plot, which involves multiplying the number of stems per meter, the number of rows, the length of each row (m), the height of each stem (m), and the weight of each stem (kg) by the plot area. Production results, such as the amount of sugar, were obtained after the factory's processing process. Sugarcane quality, including juice Brix% recorded using a brix refractometer, Pol% determined using a polarimeter, and pH measured with a pH meter, was assessed in the laboratory of Takalar Sugarcane Factory.

2.5. Statistical analysis

The statistical differences between soil depths and cultivation systems was carried out using a two-way Analysis of Variance (ANOVA) with a p-value <0.05. When the effect of the treatment is significant, it is compared with a further test using Tukey Honest Significant Differences (Tukey HSD) with p-value <0.05. Analysis was carried out using RStudio 2023.03.0+386 software. Pearson correlation was used to identify the correlation between soil properties and sugarcane yield.

3. Results

3.1. Soil texture and soil organic carbon

The laboratory analysis results show that the soil in Takalar has a higher percentage of silt and clay than that of sand, so it is categorized as silty clay soil (Table 2). Overall, the low organic C content ranges from 1.5–1.7%. The highest COLE value is in plot C, namely 0.046, and the lowest is in plot D, around 0.025. As expected, COLE values increased at low organic carbon contents.

Table 2.
Relationship between soil texture, organic carbon, and Coefficient of Linear Extensibility (COLE)

Sampling location	Soil Texture				C-Organic (%)	COLE
	Sand	Silt	Clay	Texture Class		
	%					
A	7	53	40	Silt Loam	1.60	0.034
B	10	51	39	Silty Clay Loam	1.56	0.042
C	10	65	25	Silty Clay	1.64	0.046
D	8	52	40	Silty Clay	1.72	0.025
E	25	53	22	Silt Loam	1.52	0.036

3.2. Soil bulk density and permeability

The post-tillage bulk density value is lower than the pre-tillage value. At pre-tillage, the bulk density was significantly higher at a depth of 15–30 cm compared to the bulk density value at a depth of 0–15 cm (Fig. 2a). In plots P5 and P6, the bulk density value indicated soil compaction was >1.3 g cm^{-3} (Figure 2a). In contrast, there is no significant difference existed between 0–15 and 15–30 cm depths in post-tillage (Fig. 2b). These results show that the bulk density value becomes uniform after tillage. Also, soil processing did not affect the bulk density value at a soil depth of 0–15 cm (Figure 2c). On the other hand, soil process-

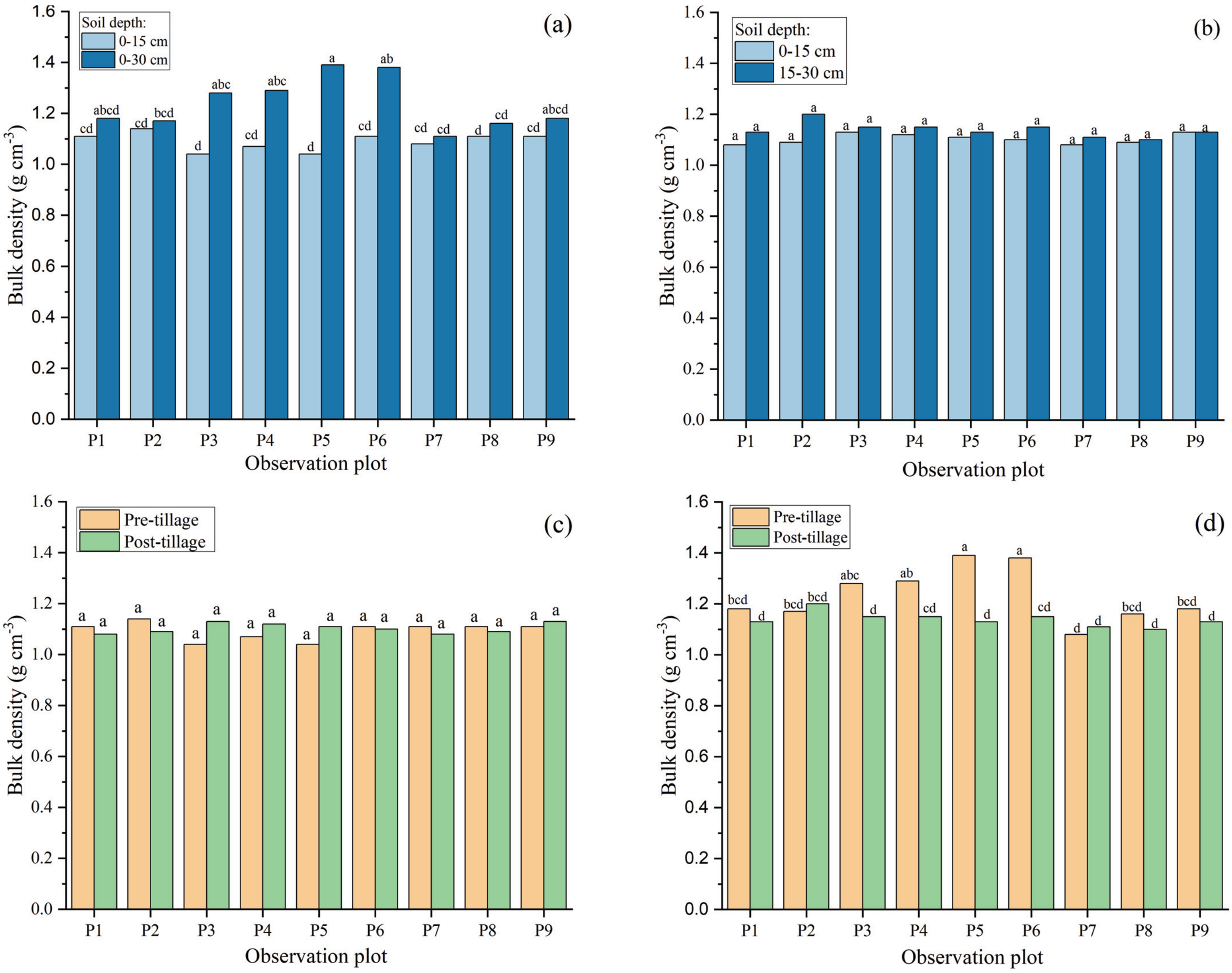

Fig. 2. Soil bulk density (a) pre-tillage at a depth of 0–15 and 15–30 cm (b) post-tillage at a depth of 0–15 and 15–30 cm (c) comparison of pre-tillage and post-tillage at a depth of 0–15 cm (d) comparison of pre-tillage and post-tillage at a depth of 15–30 cm. Different letters indicate significant difference between the treatment means using Tukey's honesty significant difference test at $p < 0.05$.

ing had a significant impact on the soil permeability value at a depth of 15–30 cm. In plots P5 and P6, where the bulk density value was previously >1.3 g cm^{-3}, it decreased to <1.2 g cm^{-3} (Fig. 2d). However, the bulk density value in the research plot did not indicate soil compaction after tillage.

In the same research plot, low permeability values were obtained, indicating significantly higher soil permeability values at 0–15 cm compared to a depth of 15–30 cm (Fig. 3 a–d). In pre-tillage, plots P7, P8, and P9 have significant differences compared to the other plots at a depth of 0–15 cm (Fig. 3a). Meanwhile, at post-tillage, permeability in plot P7 at a depth of 0–15 cm was higher than in other plots (Figure 3b). However, if a comparison is made between pre-tillage and post-tillage at a depth of 0–15 cm, the results show that the permeability in pre-tillage is higher than post-tillage (Figure 3c). Then, what is interesting from our findings is that plot P7 has higher permeability values at depths of 0–15 and 15–30 cm compared to other plots (Fig. 3). Plot P7 has a permeability value before tillage at depth 0–15 cm, measured at 7.7 cm hour^{-1}. Furthermore, the permeability of plot P7 decreased to 4.48 cm hour^{-1} after soil preparation (Fig. 3c). At a depth ranging from 15 to 30 cm, no significant differences were observed except for plot P7. However, permeability values were still declined, as shown in Figure 3d. This value shows that soil processing has the potential to reduce permeability.

3.3. Sugarcane growth

In general, there are variations in growth patterns observed in each observation plot. If plot P7 is compared with other plots, it can be seen that plot P7 shows the best growth. The number and height of stems in plot P7 is greater than in other plots. Meanwhile, the lowest growth was in plot P5. Among many growth metrics, it can be seen that the P5 plot shows the lowest number of stems and the shortest stem height (Fig. 4). There is a negative correlation between stem height and plant diameter, larger plants tend to show smaller diameters than shorter plants.

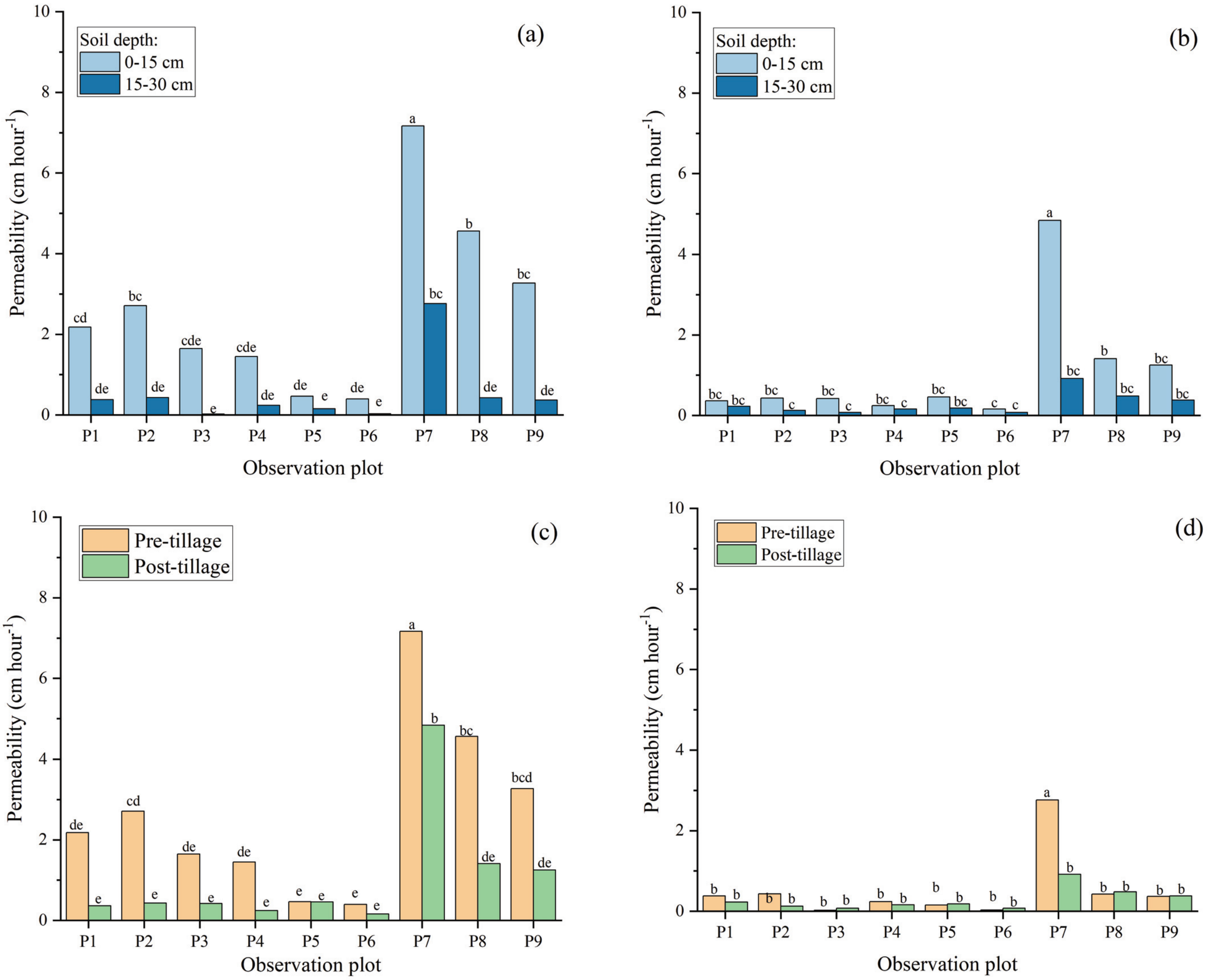

Fig. 3. Soil permeability (a) pre-tillage at a depth of 0–15 and 15–30 cm (b) post-tillage at a depth of 0–15 and 15–30 cm (c) comparison of pre-tillage and post-tillage at a depth of 0–15 cm (d) comparison of pre-tillage and post-tillage at a depth of 15–30 cm. Different letters indicate significant difference between the treatment means using Tukey's honesty significant difference test at $p < 0.05$.

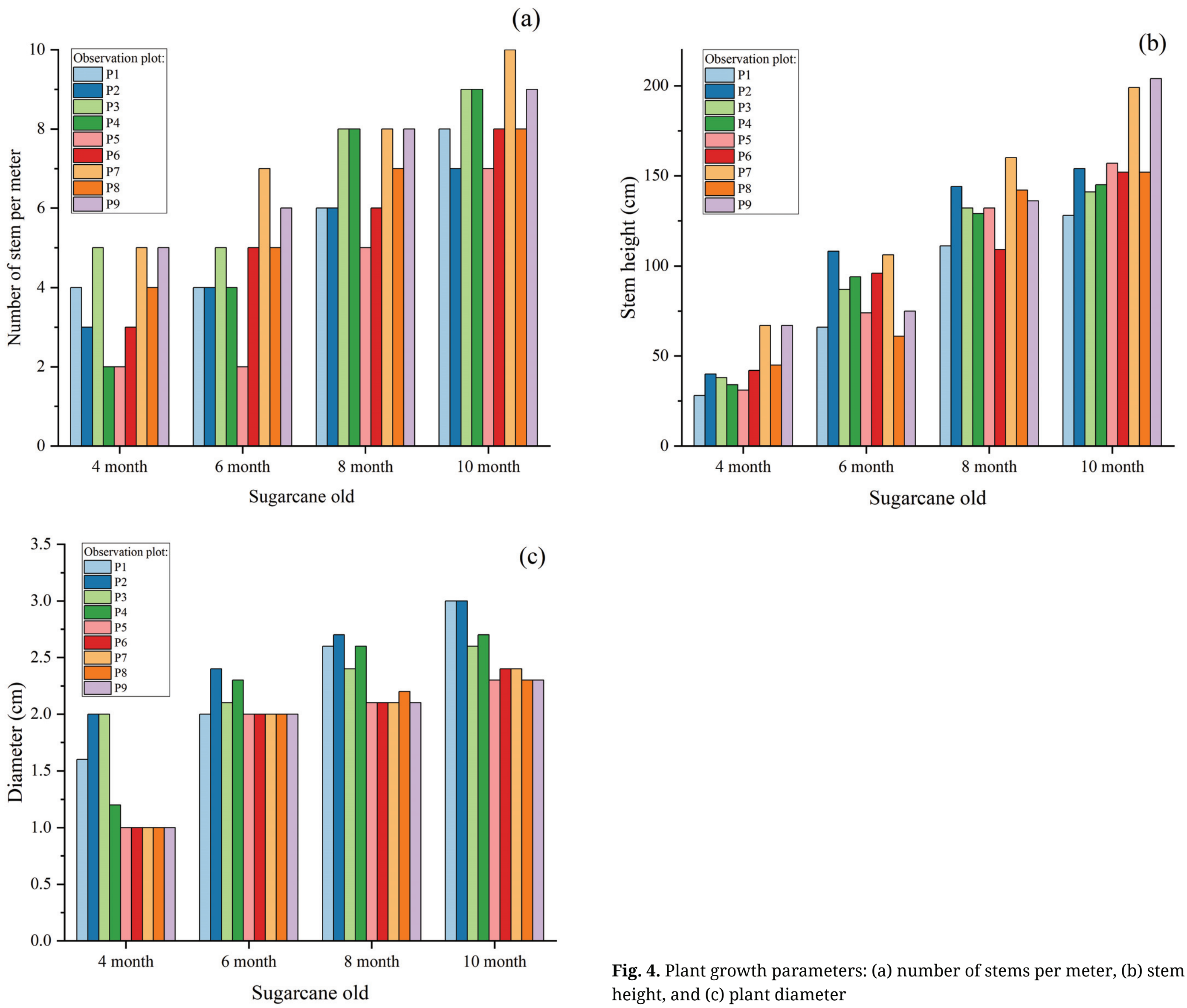

Fig. 4. Plant growth parameters: (a) number of stems per meter, (b) stem height, and (c) plant diameter

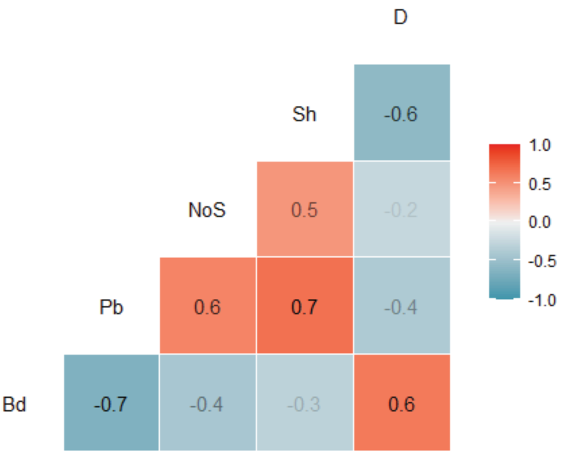

Fig. 5. Correlation between soil physical properties and plant growth parameters. Stem diameter (D), Stem height (Sh), Number of Stem (NoS), Permeability (Pb), and Bulkdensity (Bd)

Figure 5 shows the relationship between bulk density (Bd), permeability (Pb), number of stems per meter (NoS), stem height (Sh), and diameter (D). There is a positive correlation between Sh and Pb, NoS and Pb, and D and Bd. From Figure 5 it can be seen that bulk density is only positively correlated with plant diameter. This positive correlation shows that the higher the specific gravity, the larger the stem diameter. If the soil becomes dense, characterized by high bulk density, the roots cannot penetrate deep into the soil, so the stem growth will be short but large in diameter. The most obvious negative correlation, namely –0.7, between Pb and bulk density indicates the slow movement of water in the soil due to the high bulk density value. Rainwater will have difficulty seeping into the soil, so the soil becomes waterlogged during the rainy season and is susceptible to surface erosion. Shallow soil conditions with high bulk density values and low permeability can cause low plant productivity. A correlation value of –0.6 between NoS and Pb indicates that plants require soil conditions with high permeability values.

3.4. Sugarcane yield

Harvest prediction results based on plant productivity differ for each plot (Table 3). In general, production yields on plot P7 are higher compared to other plots. If all sugarcane growth is uniform, as in plot P7, then production can reach 49.11 tons ha^{-1}, whereas if plant growth is like in plot P5, production will only reach 22.42 tons ha^{-1}. The comparison of production results in plots P7 and P5 is 54.34%. The average predicted harvest yield in one hectare of land is 35.26 tons ha^{-1}, following the actual harvest yield, which is weighed directly before the sugar cane is ground in the factory, namely 35.88 tons ha^{-1} (Table 4).

The Brix value of sugar cane at harvest is 18%, indicating that the sugar cane is ripe enough to be harvested. Polarization (Pol) is a metric for quantifying the level of contaminants within a sugar sample, the lower the pol, the greater the impurity of the sample (Mastafa et al., 2020). Pol is 13.86%, with a purity cane juice value of 12%. The pH of the sugar cane produced is acidic, namely 5, and the yield is 6.79%. Based on the quality of the sugar cane obtained, the amount of sugar produced is very low, namely only 2.44 tons ha^{-1}.

Table 3.
Prediction of sugarcane production in each observation plot

Plot	Stem weight (kg)	Yield Prediction (ton ha^{-1})
P1	0.35	34.62
P2	0.39	32.32
P3	0.39	29.53
P4	0.36	30.40
P5	0.36	22.42
P6	0.36	25.41
P7	0.36	49.11
P8	0.48	46.77
P9	0.48	46.77
Mean	0.39	35.26

Table 4.
Sugarcane production parameters

Indicator	**Yield**
Sugarcane Productivity (ton/ha)	35.88
Mutu	B
Brix (%)	18.03
POL (%)	13.86
pH	5
NPP (%)	12.9
Hablur (ton/ha)	2.44
Rendemen (%)	6.79

4. Discussion

Soil quality is very dependent on the physical properties of the soil, such as organic carbon value, bulk density, and permeability. In general, fertile soil has a organic carbon content of 3–5% (Xie et al., 2023). In contrast, at the research location, the organic carbon content was below 2% (Table 1), which is categorized as low. Organic deficiency is a characteristic of marginal soils, especially silty clay soils (Wood et al., 2003). Even though the organic carbon content is low, the COLE value shows that the soil is still not dangerous for plants because it is below 0.08 to >0.14 (USDA-NRCS, 2002). If the COLE value is high, the soil will crack easily (Yan et al., 2022) and be dangerous for plant roots (Vaught et al., 2006). The COLE value can describe soil physical changes such as soil shrinkage and swelling due to variations in water content (Rehman et al., 2020; Vaught et al., 2006; Yan et al., 2022).

Besides impacting COLE values, organic C affects soil density, especially in the 0–30 cm tilled layer (Grossman and Reinsch T.G., 2002). In silty clay soil, soil density is usually seen at a bulk density value of >1.3 g cm^{-3} (Indoria et al., 2020; McCarty et al., 2015; Raper, 2005; Yue et al., 2021). In the research results, the P5 and P6 plots have a bulk density value, which indicates that compaction occurred in the pre-tillage at a depth of 15–30 cm (Fig. 2a). However, the bulk density value decreased and was uniform in all observation plots post-tillage (Fig. 2b). There is no significant difference between pre-tillage and post-tillage at a depth of 0–15 cm (Fig. 2c). These findings confirm the report by Zhao et al. (2022), which also shows that the bulk density at a depth of 15–30 cm is significantly higher than at a depth of 0–15 cm. One possible cause is soil turning during ploughing with a tillage depth of 0–30 cm, making the soil uniform (Shah et al., 2017). In the land ploughing process, the tractor only turns over the soil in the tilled layer so that shallowing occurs in the layer below (Leye, 2007), the main characteristic of land degradation (S. Chen et al., 2022). Although the overall bulk density value at the research location does not indicate soil compaction, the permeability value is very low, which indicates that water movement in the soil is very slow (Figure 4d).

Soil permeability decreases as bulk density increases (Lipiec and Hatano, 2003), and low permeability reduces plant water supply and increases surface runoff (Batey, 2009; Indoria et al., 2020; Lipiec and Hatano, 2003). The research shows that permeability values are lower at depths of 15–30 cm (Fig. 3). These results support what other studies have found: soil depth is negatively related to permeability values (A. Chen et al., 2022; Ozcoban and Acar, 2018). The soil permeability value at post-tillage is lower than pre-tillage (Fig. 3c), indicating that soil processing can reduce the rate of water movement in the soil due to pore discontinuities (G. Chen et al., 2014). The low rate of water movement in the soil and poor drainage make it difficult for water to infiltrate, so plants will be flooded during the rainy season. Sugarcane planting at the research location began in November, which has entered the rainy season. The impact of low permeability can be seen in sugarcane growth.

The sugarcane growth parameters that we observed included the number of tillers, height and stem diameter. Observation results show that sugar cane in plots with low permeability has slower growth than other plots (Fig. 4). Plant growth in plot P5 was 28.57% shorter than in plot P7 (Fig. 4b). The height of sugarcane before harvest at the research location was around 150–200 cm, which indicates abnormal growth (Fig. 4b). Previous studies reported sugarcane height ranging from 2.5 m to 3.5 m at 240–360 days after planting (De Souza et al., 2017; Molijn et al., 2019), and depending on the variety, sugar cane is normally 2.5–5.0 cm in diameter (James, 2004). These results indicate that low permeability greatly affects plant growth. In addition, the diameter is larger in the stems of taller plants, and the number of stems is smaller. Misra et al. (2020) have reported that sugarcane diameter and stem growth decreased by 18.28% in drought conditions and 11.41% in flooded conditions. The results in Figure 4a-d show that stem diameter increases as bulk density increases and is negatively correlated with height and number of stems.

Based on the results of plant growth parameters, predictions of crop production can be made as shown in Table 3. If plant growth in one hectare of land is like in plot P5, then production can only reach 22.42 tons ha^{-1}, a decrease of 67.97% and production based on growth in plot P7 is 49.11 tons ha^{-1}, a decrease of 29.84% from sugarcane production which should be 70–75 tons ha^{-1} (BPS Indonesia, 2018). Low plant productivity is triggered by water stress, which greatly affects the germination phase, early growth and ripening phase (Sanghera et al., 2019) due to shallow soil and low permeability (S. Chen et al., 2022; Ozcoban and Acar, 2018). Lack of water supply during the dry season and excess water during the rainy season due to poor drainage causes plant shoots to die (Misra et al., 2020). Silty clay soil, which has fine particles and is difficult to pass water through, is also a big problem on marginal land (Hajabbasi and Hemmat, 2000; Zhao et al., 2022).

5. Conclusions

There was an impact of soil processing on bulk density and permeability values, directly influencing plant productivity. Although soil processing could decrease the bulk density value at a depth of 15–30 cm, it failed to enhance soil permeability. The soil permeability rate at depths of 0–15 and 15–30 cm declined post-tillage, leading to compromised plant growth. In Takalar, sugarcane plants exhibited below-average growth, with insufficient plant height (below 200 cm), stem diameter (less than 3 cm), and a minimal number of stems per meter at the initial growth stage. The observed plant growth outcomes suggested inadequate nutrient absorption during the growth period, which was evident in low C-organic content values. This condition resulted in a 50% reduction in production, causing significant losses given the commercial nature of sugarcane cultivation. Consequently, further research was imperative to achieve consistent plant growth and maximize productivity. This could be accomplished by improving soil properties to ensure proper plant nutrient absorption.

Acknowledgments

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