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**Research Article**

# Implication of the root growth and soil macropores distribution on sugarcane yield in Takalar, Indonesia

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## Abstract

This study examined the relationship between the decline in sugarcane productivity and the distribution of macropores and depth of root penetration in sugarcane plantations in Takalar during one planting period (October 2021-September 2022). There were five observation points (P1, P2, P3, P4, and P5) in one hectare of land to measure the distribution of soil macropores using methylene blue solution. Cross-sections of the soil were made to observe the presence of plant roots at a depth of 0-40 cm with a width of 60 cm. In each plot, disturbed soil samples were collected to measure soil texture, soil organic matter (SOM), nitrogen (N), phosphorus (P), and potassium (K) contents. Other measurement parameters were the infiltration rate and plant productivity. The results indicated that SOM and NPK levels at the research location were deficient, serving as the first indicators of problematic soil. Macropore observations revealed that macropores were distributed only at a less than 10 cm soil depth. This distribution limited the penetration of plant roots to a depth of 0-40 cm. The root length density (RLD) value indicated the absence of roots at depths of 30-40 cm in plots P2 and P3. The field findings explained why sugarcane production in Takalar only achieved 50%, around 40 t ha$^{-1}$ from the first ratoon sugarcane harvest, instead of the expected 70-80 t ha$^{-1}$.

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## Introduction

One of the critical factors influencing sugarcane yield is the root growth system (Smith et al., 2005; Mason et al., 2022). The deep and extensive root system allows plants to survive despite low rainfall or poor irrigation (De Silva et al., 2011). Root penetration into the soil determines how much water and nutrients can be absorbed to support plant growth (Chopart et al., 2010). In a previous study, James (2004) reported that the sugarcane root system could penetrate up to a depth of four meters with a width of two meters (James, 2004). Chopart et al. (2010) also observed that in ratoon sugarcane, new cane roots replace old cane roots and can grow to a depth of 4 m. However, root distribution decreases with soil depth because roots cannot penetrate hard soil layers (Smith et al., 2005). Studies indicate that the distribution of macropores significantly influences how the sugarcane root system spreads out (De Silva et al., 2011); the absence of macropores can impede horizontal root growth (Otto et al., 2011). Although the root system serves as the crucial link between soil and plants for nutrient absorption, the relationship between macropores and root distribution still requires a better understanding (Otto et al., 2011; Bottinelli et al., 2014; Ighalo et al., 2021).

Macropores are empty spaces in the soil that facilitate the movement of water, air, and nutrients (Lipiec and Kus, 2006; Josa et al., 2013). Soil macropores serve as channels for root penetration, enabling efficient absorption of nutrients (Barton and Karathanasis, 2002). Previous research by Bottinelli et al. (2014) reported that the regeneration of soil macro porosity occurred exclusively at a depth of 0-7 cm at the soil surface, while the soil below continued to experience compaction. When soil macropores were diminished or disturbed, as in dense soils, sugarcane root growth was impeded, leading to a significant reduction in plant productivity (Smith et al., 2005; Bottinelli et al., 2014). Macropores play a vital role in influencing soil infiltration, which serves as the primary mechanism for water flow into the soil (Raper, 2005; Ma et al., 2016). According to De Silva et al. (2011), a decrease in soil water content due to low infiltration caused water stress in plants, characterized by an increase in root dry weight. The results of previous research by Safitri et al. (2024) indicated that the land in the Takalar sugarcane plantation was marginal land with a shallow depth of cultivation. However, additional investigation is still needed to examine the correlation between soil macropores and the growth of sugarcane roots. Therefore, this research was based on the hypothesis that the root system varied vertically and horizontally and was closely related to the distribution of soil macropores, which was the leading cause of reduced crop productivity.

This research aimed to demonstrate that different root distributions, even within the same field, directly influenced variations in plant growth, including plant height, diameter, and number of tillers.

## Materials and Methods

### *Study site*

The research was conducted in the sugarcane research and development fields of the Takalar sugar factory (5°22’16” S-19°29'36" E) in South Sulawesi, Indonesia (Figure 1). The study spanned the October 2021 planting season to the September 2022 harvest, focusing on the first ratoon cane. The one-hectare land area was diagonally divided to establish five observation points (Figure 2a).

### *Soil physico-chemical properties*

Disturbed soil samples were collected at five research points (Figure 2a) to measure soil texture, nitrogen, phosphorus, potassium (NPK), and organic carbon content in the soil. Soil texture measurement was conducted in the laboratory using the hydrometer method (Bouyoucos, 1962).

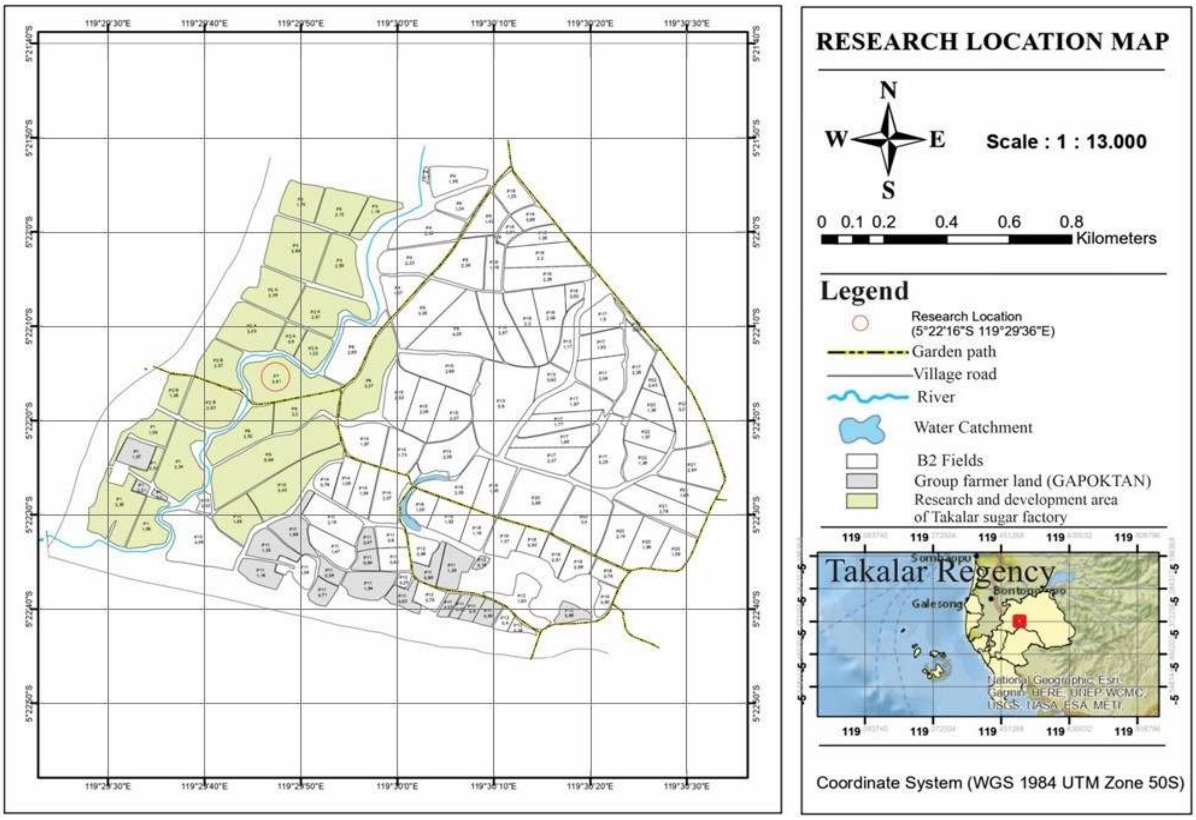

Figure 1. Research location map.

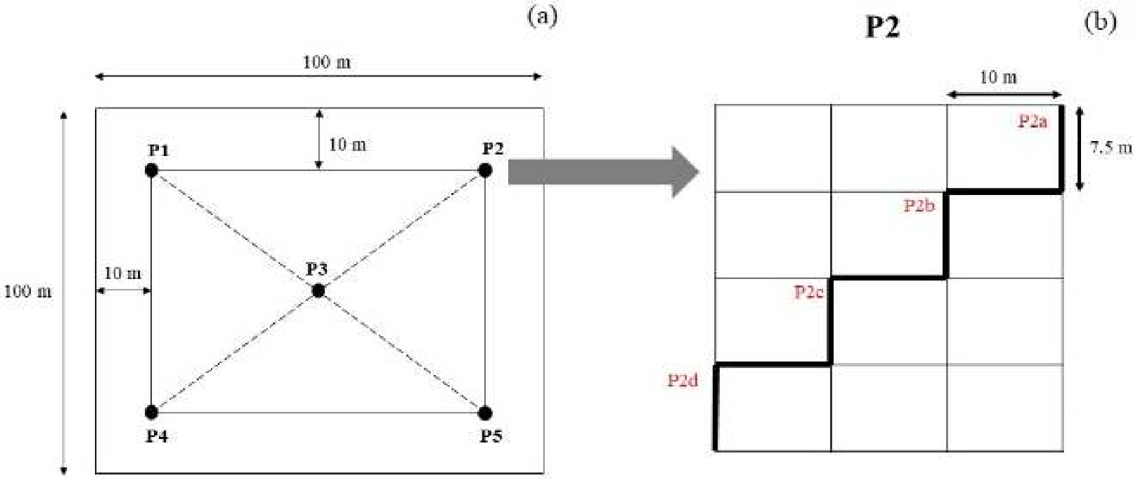

Figure 2. (a) Observation plot, (b) Zig-zag method for sugarcane growth measurement.

Organic C measurements were performed using the Walkley and Black method (Walkley and Black, 1934), and NPK measurements utilized a method based on the fundamental principles of the Kjeldahl method (Kjeldahl, 1883).

### *Soil infiltration*

The field observation procedure from Liu (2022) research method was adapted and modified using a Marriott bottle, applying the constant pressure test principle. The Marriott bottle was designed to maintain the water level in the infiltrometer ring, enabling us to measure water infiltration into the soil. In this study, a Marriott bottle with a diameter of 16 cm and a height of 150 cm, equipped with a measuring scale was used. The double-ring infiltrometer comprises two rings, each with diameters of 30 cm and 20 cm and a height of 25 cm. The infiltration rate was measured at five observation locations (Figure 2a) using a double-ring infiltrometer. The two double rings were symmetrically placed between the sugarcane plants and inserted into the soil to a depth of 5 cm (Figure 3).

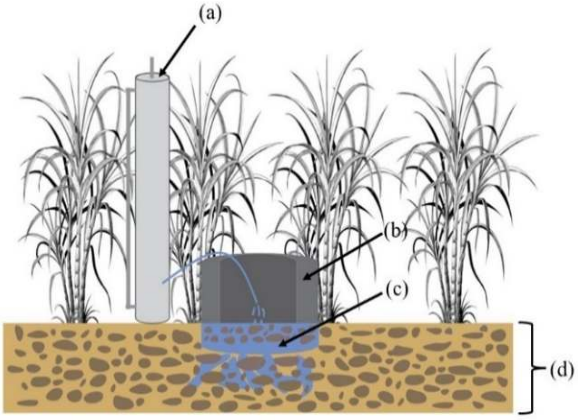

Figure 3. Illustration of infiltration measurements. (a) Marriote bottle, (b) double-ring infiltrometer, (c) methylene blue solution, and (d) soil cross-section.

Subsequently, the Marriott bottle was filled with methylene blue water at 0.04 g $L^{-1}$ (Utami et al., 2021). The Marriott bottle's working principle was maintaining a constant water level in the double ring (Chabot et al., 2002). The double-ring infiltrometer was coated with plastic and filled with the methylene blue solution to the desired water level before the measurement commenced. The plastic covering the ring was slowly removed, and the measurement began. Scale readings on the Marriott bottle were taken every 1 minute for 60 minutes. The infiltration values measured in the field were then calculated using the Kostiakov model (Zakwan et al., 2016; de Almeida et al., 2018).

$$I = Mt^n$$

where:

I = cumulative infiltration rate
n = index of soil structural stability
M = a measure of the initial rate of infiltration and structural condition of the soil

### *Soil macropores*

After 24 hours of infiltration observation, the double ring was carefully removed from the soil to prevent damage to the soil surface, following the methodology outlined in previous research by Utami et al. (2021). Subsequently, a cross-section with dimensions of 40 cm by 60 cm was created, featuring vertical slices for macropore observation. The soil matrix absorbed the methylene blue that passed through the micropores but left a blue color in the macropores (Utami et al., 2021). Tracing the macropore patterns left by methylene blue required using plastic the same size as the observed cross-sectional area (Figure 4). The resulting images were then digitized, and the colored areas were calculated using the ImageJ program to predict the macropore area.

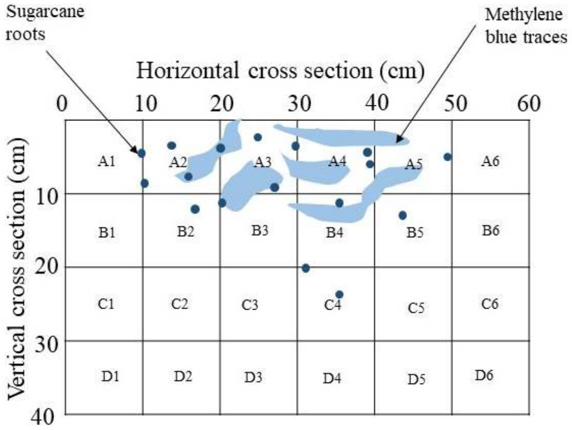

Figure 4. Cross-sectional measurements of root distribution and soil macropores.

### Root morphology

Observations of plant roots were conducted after the macropore examination. Plant roots visible in the soil cross-section were identified and marked on a 40x60 cm plastic sheet with a 10x10 cm grid using a marker (Figure 4). The resulting images depicting the distribution of root points were mapped and digitized using Corel Draw x7. Root samples were obtained using a 10x10x2 cm box-shaped tool. Sugarcane roots were separated from the soil samples through washing and filtering, and they were then collected based on the observation plots (A1-D6). The collected roots were arranged in millimeter blocks of paper, and their lengths were measured using ImageJ tools. The root samples were then dried in an oven at 70°C for approximately 24 hours, following the method described by Pissolato et al. (2021).

### Sugarcane productivity

Plant productivity was assessed every two months, beginning when the sugarcane was four months old and continuing until harvest. According to research by Misra et al. (2020), the parameters evaluated include plant height, number of tillers, and plant diameter. The zig-zag pattern in Figure 2b was depicted using the measurement method outlined by Wood et al. (2003). By applying the Takalar sugar factory standard operating procedures (SOP), it is possible to calculate the anticipated harvest production for each plot by multiplying the number of stems per meter, the number of rows, the length of each row (in meters), the height of each stem (in meters), and the weight of each stem (in kilograms) with the plot area. Production results, such as the amount of sugar, were obtained after the factory's processing process. Sugarcane quality, including juice Brix percentage, was recorded using a brix refractometer, POL (polarization) percentage was determined using a polarimeter, and pH measured with a pH meter, was assessed in the laboratory of Takalar sugar factory. The actual harvest results were obtained through measurements taken in both the laboratory and the factory.

### Statistical analysis

Data analysis for sugarcane productivity was performed using a two-way analysis of variance (ANOVA) with a significance level set at $p<0.05$. If the treatment showed a significant effect, it was further compared through a subsequent test using Tukey Honest Significant Differences (Tukey HSD) with a significance level of $p<0.05$. The analysis was carried out using RStudio software version 2023.03.0+386.

## Results and Discussion

### Soil physico-chemical properties

The research results demonstrate that the soil at this location has deficient organic carbon, nitrogen, phosphorus, and potassium (NPK) contents (Table 1). There were no significant differences in organic carbon and NPK content across all research plots. However, the lowest content was observed at point P3. This value indicates that the soil in the central part of the land (P3) has a lower nutrient content compared to the edge of the land (P1, P2, P4, P5) (Figure 2). The relationship between organic carbon, soil texture, and NPK is complex and interconnected, impacting soil fertility and productivity. Sandy soils typically have a lower organic carbon content because they do not retain organic matter as effectively as finer-textured soils such as clay or loam. Clay soils, with their smaller particle size, exhibit higher nutrient capacity, influencing the availability of NPK for plants (Ugarte Nano et al., 2016; Zhou et al., 2019).

Nitrogen (N) is crucial for the formation of chlorophyll and amino acids; phosphorus (P) is a vital component of DNA; and potassium (K) plays a crucial role in activating enzymes in plants (Potdar et al., 2021). Deficiency in NPK directly impacts plant growth, especially in developing roots, stems, and leaves (Nabel et al., 2017). In sugar cane plants, a nitrogen deficiency can cause the leaves to change from green to yellow, and insufficient phosphorus can result in shorter stems, fewer tillers, and disturbance in the growth of lateral roots.

In contrast, potassium deficiency leads to decreased plant production, as potassium is essential for sugar translocation (Mangrio et al., 2021). High rainfall on marginal land causes leaching, which results in a deficiency in the soil's organic C and NPK content (Nabel et al., 2016). The development of a crust on the soil's surface layer, which results in nutrient leaching (Utami et al., 2021), is a phenomenon that the soil texture significantly affects (Chen and Weil, 2011).

Table 1 indicates that the soil at the observation location has a silty clay texture, characterized by its difficulty in allowing water passage due to the lack of macropores (Rawls et al., 2003). Soil texture also plays a pivotal role in soil fertilizer decomposition; previous research has reported that soil texture influences litter decomposition and organic matter mineralization (Josa et al., 2013; Kane et al., 2023). Other studies suggest that nutrient decomposition is faster in sandy clay soil than in silty clay soil due to the higher bacterial diversity in sandy soil (Zheng et al., 2021).

Table 1. Soil physico-chemical properties.

| Observation plots | Soil Texture | | | | Organic C (%) | N (%) | C/N | P (ppm) | K (cmol kg$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| | Sand (%) | Silt (%) | Clay (%) | Texture Class | | | | | |
| P1 | 7 | 53 | 40 | Silty Clay | 1.52 | 0.08 | 7 | 6.79 | 0.48 |
| P2 | 10 | 65 | 25 | Silty Loam | 1.34 | 0.08 | 6 | 6.45 | 0.26 |
| P3 | 10 | 51 | 39 | Silty Clay Loam | 1.27 | 0.05 | 3 | 6.13 | 0.18 |
| P4 | 8 | 52 | 40 | Silty Clay | 1.95 | 0.15 | 12 | 7.94 | 0.47 |
| P5 | 5 | 53 | 48 | Silty Clay | 1.72 | 0.26 | 9 | 6.03 | 0.30 |

***Soil infiltration rate***

The findings of this study generally indicate variations in the infiltration rate across one hectare of flat land. Figure 5 illustrates the infiltration rate measured at five observation points within the hectare. Notably, point P4 exhibits the highest infiltration rate at 3.63 cm hour$^{-1}$, while the lowest infiltration rate is observed at point P3, measuring 1.35 cm hour$^{-1}$. The infiltration rates at observation points P1 and P2 are relatively similar, ranging around 1.98 cm hour$^{-1}$. This value underscores the fact that the infiltration rate is influenced by the specific observation location and the physical properties of the soil (Igboekwe and Adindu, 2014), particularly the soil texture, which is determined by the percentage of sand, silt, and clay in the soil (Natural Resources Conservation Service U.S, 2014).

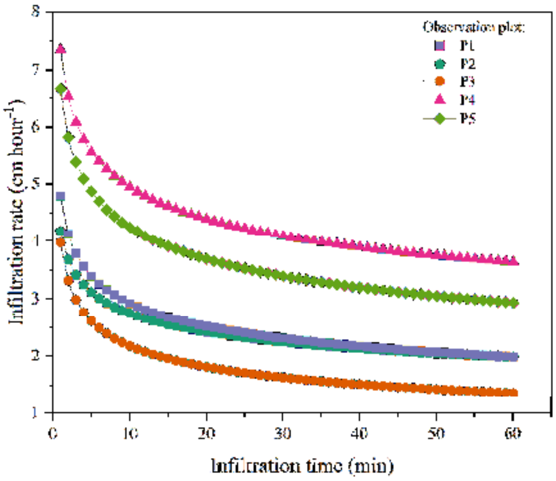

Figure 5. Soil water infiltration observed and estimated (cm hour$^{-1}$) in time (minute) by Kostiakov-Lewis (cm hour$^{-1}$).

Sandy soil texture generally exhibits a higher infiltration rate than silty clay soil (Ma et al., 2016). Upon examination of the soil texture in Table 1, it is evident that the research location has a low percentage of sand and is predominantly composed of silt and clay. This composition accounts for the observed low infiltration rate at the research site. Furthermore, the influence of organic C content on the infiltration rate is noteworthy. A low organic C content negatively impacts soil structure, leading to reduced infiltration rates (Franzluebbers, 2002; Boyle et al., 2013; Muharyani et al., 2019).

***Soil macropores and distribution roots***

The application of a methylene blue solution to the soil facilitates the staining of soil macropores (Lipiec and Kus, 2006; Utami et al., 2021). As illustrated in Figure 6, traces of methylene blue were detected at five observation points, exclusively at depths less than 10 cm. This observation indicates that soil macropores are primarily concentrated in the top layer. Notably, at point P4, macropores were still distributed within the 0-10 cm depth range, while at points P2 and P3, macropores were found only up to a depth of 5 cm. According to de Almeida et al. (2018), this distribution pattern is consistent with the findings in Figure 5, which show a correlation between low macropores and inhibited infiltration rates.

The points marked on the observation plot (Figure 4) illustrate the distribution of roots within the observed area. The results of the observations indicate a decrease in the number of root distributions with increasing soil depth. In contrast to the findings from Chopart et al. (2010), where ratoon sugar cane roots were reported to reach a depth of 4 m, the field observations do not support this claim. The root distribution observed at a depth of 0-40 cm reveals minimal root presence, challenging the idea that sugarcane roots in Takalar can grow to a depth of 4 m. Furthermore, in plot P3, the distribution of roots is both horizontally and vertically limited. This observation aligns with the earlier finding of minimal macropore visibility beyond depths of 10 cm (Figure 6).

Root length density (RLD), measured in the observation plot (Figure 2), revealed a consistent decrease in RLD values with increasing soil depth (Figure 7). Notably, the P4 observation plot exhibits the highest RLD overall, with a value of 0.15 cm cm$^{-3}$ at a depth of 0-10 cm. In contrast, the lowest RLD was observed in the P3 observation plot, registering at 0.05 cm cm$^{-3}$. Concerningly, no roots were found at a depth of 30-40 cm at observation points P1 and P3. Additionally, other observation points exhibit very low RLD values at a depth of 30-40 cm, indicating minimal root presence at that depth. These findings suggest that the majority of sugarcane roots are concentrated in the shallow soil layer. This observation aligns with the findings of De Silva et al. (2011), who reported the highest RLD value at a soil depth of 0-30 cm. Similarly, Nixon and Simmonds (2004) noted that within the observation range of 0-60 cm, 39-45% of plant roots were at a depth of 30-60 cm, while 65-74% were concentrated in the top depth (0-30 cm). However, this study's RLD value, when compared to De Silva et al. (2011) results, appears significantly lower, indicating a potential issue with root growth at the research location.

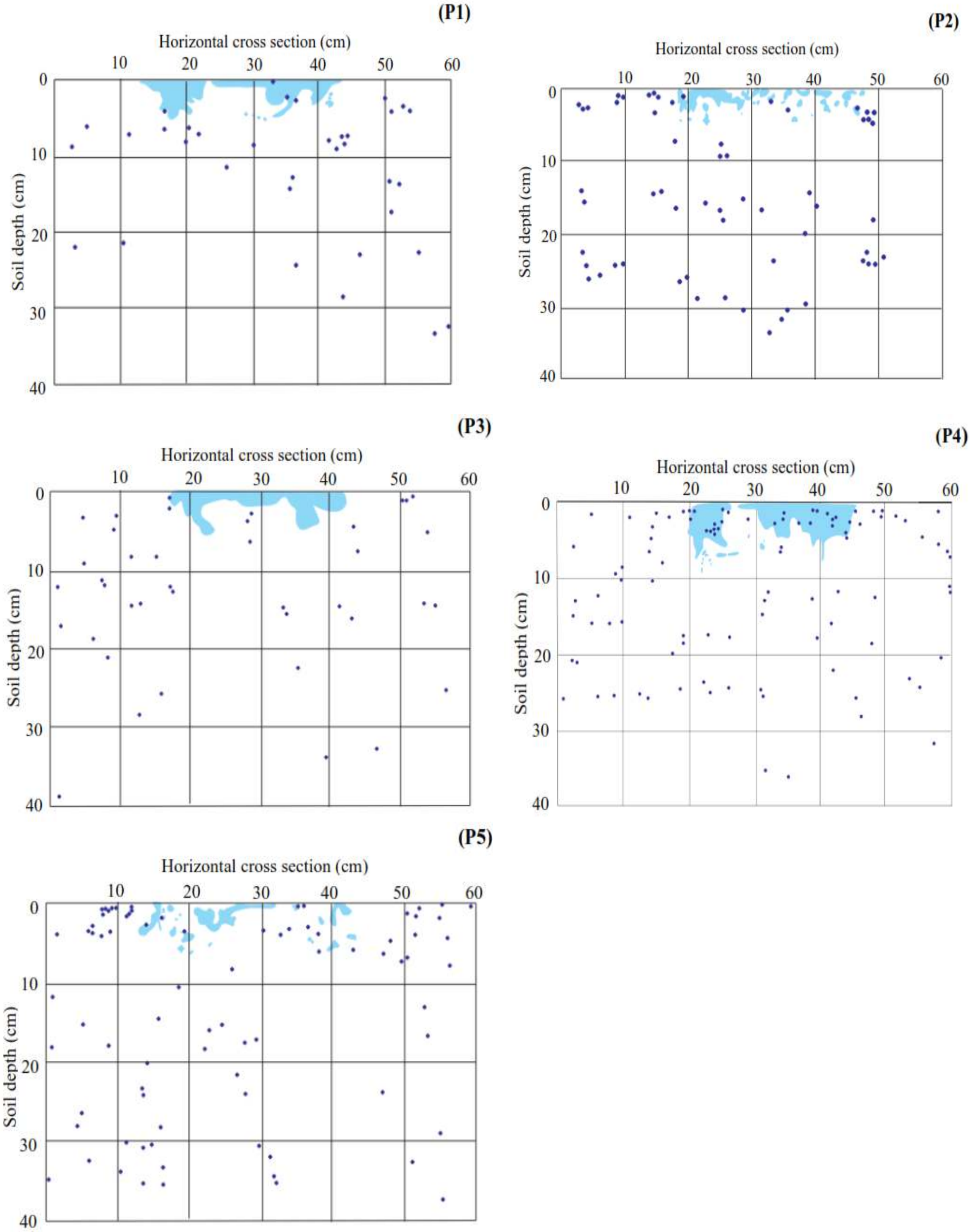

Figure 6. Soil macropores and root distribution.

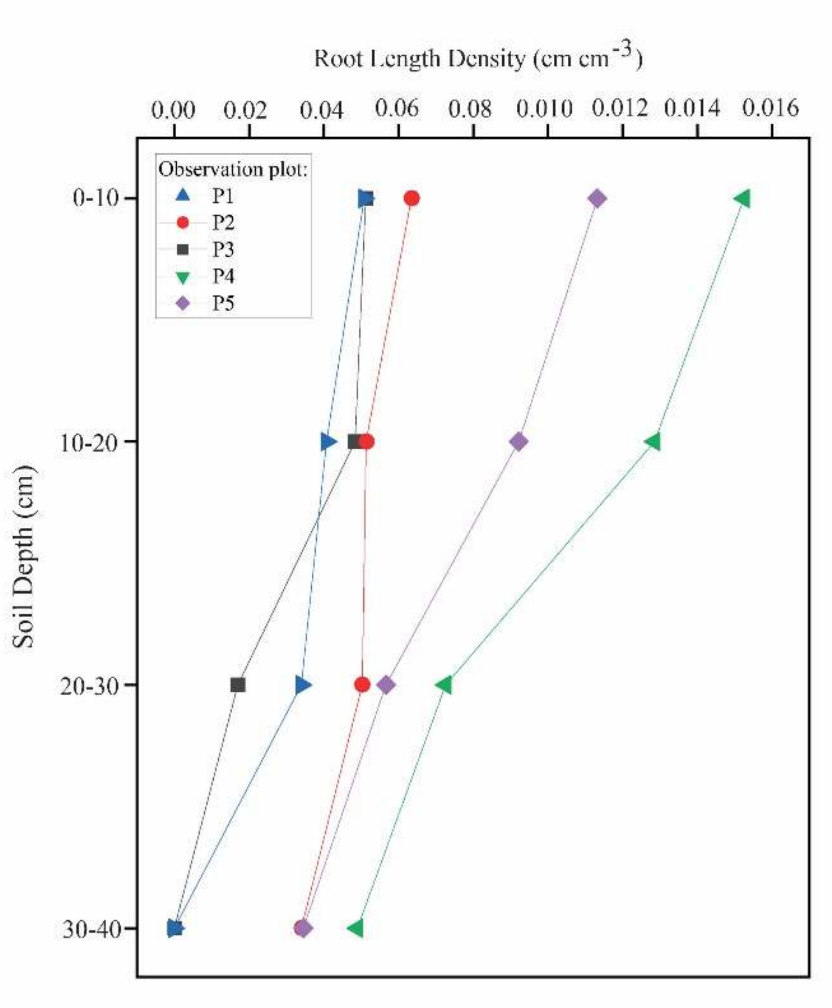

Figure 7. Root length density (RLD).

***Sugarcane productivity***

Plant height, the number of tillers, and stem diameter measurements were taken from the time the sugar cane reached four months old until harvest. Overall, no significant differences were observed at observation points P1, P2, and P3 (Figure 8). However, significant differences were noted at points P4 and P5 concerning plant height, the number of tillers, and stem diameter.

In plot P4, the highest number of saplings in one plant clump was recorded, totaling 13 tillers, while the lowest counts were observed at points P2 and P3, each with 7 tillers (Figure 8). It is worth noting that the observed size and characteristics of sugarcane plants did not align with typical sugarcane growth patterns. Typically, sugarcane can reach a height of 2 m or more with a diameter exceeding 3 cm (James, 2004; Gregory, 2007). This discrepancy raised concerns about the normal growth and development of sugarcane at the research location.

The root system played a crucial role in fostering the growth of new roots in ratoon sugarcane, serving as the primary source of carbon and energy for early plant development (Pissolato et al., 2021). Previous research elucidated the impact of root biomass on sugarcane growth, particularly influencing stem height and diameter (Portz et al., 2012; Pissolato et al., 2021). However, the research results (Figure 8) indicated that plant growth deviated from expectations.

The data in Table 2 demonstrate that this condition led to low productivity, as one hectare of land could only produce 40 tons of sugarcane. This yield was below the expected production of 70-80 t ha$^{-1}$ for well-growing sugarcane (BPS Indonesia, 2018). The quality of the harvested sugarcane was classified as grade B, determined based on inspections according to the operational standards of the Takalar sugar factory. The Brix, or total soluble solids, percentage in the juice indicated that the sugarcane was harvested when ripe, with a polarization (POL) of over 12%, meeting the standard sugar content. However, the sucrose content only reached 3.22 t ha$^{-1}$, falling far below 6 t ha$^{-1}$ standard and producing very low sugar. Additionally, the yield produced was only 7.5% lower than the average yield of normal sugarcane, which typically exceeded 8% (Tewari and Irudayaraj, 2003; BPS Indonesia, 2018; Mastafa et al., 2020; Saetear et al., 2021).

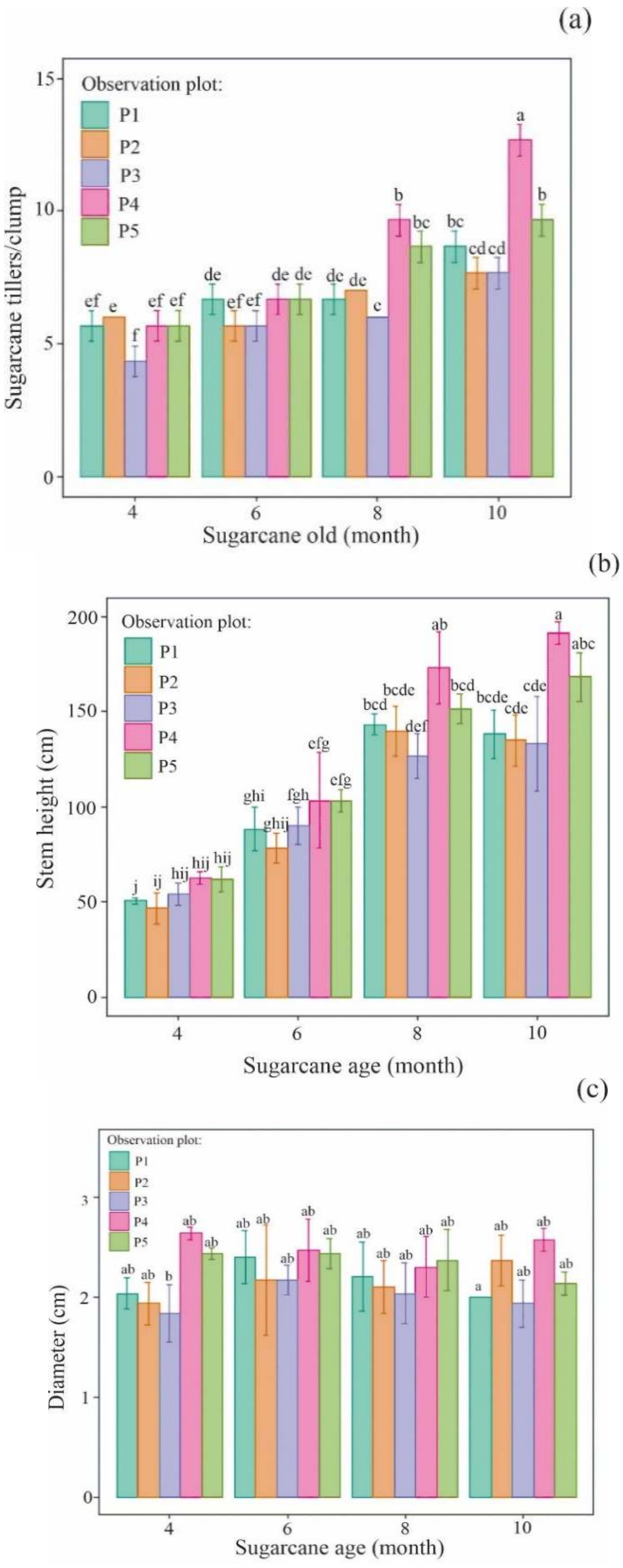

Figure 8. Sugarcane productivity during one growing season.

Table 2. Sugarcane yield.

| Indicator | Yield |
|---|---|
| Sugarcane productivity (t ha$^{-1}$) | 40 |
| Quality | B |
| Brix (%) | 18.12 |
| POL (polarization) (%) | 14.75 |
| pH | 5.2 |
| Sucrose content (t ha$^{-1}$) | 3.22 |
| Rendemen (%) | 7.5 |

## Conclusion

A deficiency in the distribution of soil macropores caused a decline in sugarcane production in Takalar. This deficiency hampered the penetration of sugar cane roots, confining them to a depth of 0-40 cm. The Root Long Density (RLD) value showed that roots at points P2 and P3 did not extend beyond 30 cm. The subpar growth of sugar cane, reflected in factors such as a stem diameter of less than 3 cm, a stem height below 200 cm, and a limited number of cane saplings, substantiated this observation. In addition to root limitations, the soil displayed low levels of organic carbon (C) and NPK content. Moreover, the soil's infiltration rate was notably low, registering only 3.36 cm/hour. This low infiltration rate could cause waterlogging during the rainy season, further impacting sugar cane cultivation.

## Acknowledgments

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