SOIL CHEMICAL VARIATION AFFECT RUBBER PRODUCTIVITY IN STATE ENTREPRISES PLANTATION

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ABSTRACT

Variations in rubber production are thought to be influenced by differences in soil fertility. The study aimed to analyze and evaluate soil fertility variation in different rubber productivity. The research was conducted from January to June 2024 in Banjarsari Plantation, PT Perkebunan Nusantara I Regional 5 Jember Regency, especially at two contrast rubber productivity (i.e., high and low productivity). The classification of rubber productivity determined from the average rubber production during the last 3 years before the research, namely land with high productivity has a production ≥ 1,500 kg ha^{-1}, while land with low productivity has a production ≤ 1000 kg ha^{-1}. All the research plot was located at 12-13 years old of rubber which is cultivated in monoculture systems, especially at clone RRIC-100. Soil sample were collected on a plot size 20 m × 20 m at 2 depths (i.e., 0-20 cm and 20-40 cm) of the high and low rubber productivity with 3 replications of each. Soil chemical properties were measured, including soil organic C, pH, total N, available P, soil exchangeable K, Ca, Mg, Na, Cation Echange Capacity (CEC), and base saturation (%). The study found that the land with high rubber productivity had 72-85% higher of soil exchangeable Na as compared to the land with low rubber productivity at 0-20 cm and 20-40 cm depths, as well as had 46% higher of total N at the top 20 cm of soil. In contrast, the land with low rubber productivity had 41% and 11% higher of soil exchangeable K and Ca as compared to the land with high rubber productivity, probably due to the high K and Ca uptake for supporting rubber production. Pearson correlation and principal component analysis (PCA) test highlighted the significant relationship between functional elements such as soil exchangeable Na and latex production ($r = 0.82$, r table 5% = 0.497, p-value = 0.001). Therefore, increasing soil fertility through combining organic and inorganic fertilizer containing N and Na (e.g., potassium nitrate or borate fertilizers) can be helpful in areas with low rubber productivity for sustainable rubber production.

Keywords: Monoculture rubber plantation; Rubber productivity; Soil chemical properties; Soil management

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INTRODUCTION

Rubber (*Hevea brasiliensis*) is an export commodity that contributes to the increase in Indonesia's foreign exchange. Indonesia is the second largest rubber producer in the world, having 2.7 million tons of rubber export per year (from the period 2014 – 2019) and 28.7% market share in the world (Zuhdi and Anggraini, 2020). However, Indonesian Statistics Bureau reported that total volume of rubber export (natural and synthetic) from 2013 to 2023 has declined up to 30% (BPS, 2024). This was probably related to the decreases of Indonesia rubber production in 2023 as compared to 2013 around 31% (~996,607 tons of rubber).

State owned enterprises of rubber plantation, covers an area of 122879 ha or 8.5% of total rubber plantation area in Indonesia, has experienced in declining productivity from 1.05 ton/ha in 2013 become 0.8 ton/ha in 2023 (BPS, 2024). The decreases in rubber productivity is possibly related to soil fertility degradation, especially the low of soil nutrient availability (i.e., C, N, P, K, Ca, Mg). Vrignon-Brenas *et al*. (2019) stated that soil chemical properties influence rubber tree growth and latex yield by regulating nutrient uptake efficiency and overall physiological processes. In addition, Ogidi *et al*. (2018) reported that the balance of macro- and micronutrients within the soil significantly influences the growth, vigor, and consequently, the latex yield of rubber trees. The other research by Fatmawati *et al*. (2021) showed that the low concentrations of essential elements such as phosphorus (P), potassium (K), and organic carbon, are often exacerbated by soil acidity and agricultural practices.

Beside essential nutrients, functional elements (i.e., Na) plays an important role on rubber productivity. Sodium (Na) has been studied for its potential to substitute for potassium in certain physiological processes, thereby offering a possible strategy to mitigate nutrient deficiences and reduce reliance on potassium fertilizers in rubber cultivation (Thorne and Maathuis, 2022). While, Battie-Laclau *et al*. (2016) and Mateus *et al*. (2021) stated that Na contributes to osmotic adjustment, stomatal regulation, and turgor maintenance, which are vital processes for optimizing water use efficiency and photosynthesis performance in rubber trees. However, Na is easier losses through leaching, necessitating careful management strategies to maintain adequate availability for plant uptake (e.g., rubber) while preventing environmental runoff (Nieves-Cordones *et al*., 2016). This situation necessitate a thorough understanding of the relationship between soil nutrient status and rubber tree performance to optimize fertilization strategies and improve overall productivity (Kullawong *et al*., 2020; Saeteng *et al*., 2022).

The response to fertilization in rubber plants depends on their nutrient status. Salisu *et al*. (2013) stated that knowledge on soil nutrient status helps in proper fertilization in rubber plantation, as different soil fertility respond differently to the fertilizers. Under nutrient deficiency conditions, rubber plants are highly responsive to fertilization, which can further increase growth and production. One area of rubber plantations with low productivity suspected to be related to soil fertility levels is the Banjarsari Plantation Jember, PT Perkebunan Nusantara I Regional 5, planted in 2013. The total area of mature rubber trees (TM) at the Banjarsari Plantation is 638.41 ha, with an average annual production of 992,631 kg. Although the overall average productivity is categorized as high (1,555 kg/ha), a significant yield gap exists in the field. On one hand, there are blocks with high productivity (≥ 1,500 kg/ha), while on the other, several blocks show low productivity (≤ 1,000 kg/ha) despite being under the same management. This productivity gap serves as the basis for evaluating whether soil chemical factors are the primary cause of these yield differences. In addition, all block with different rubber productivity did not applied fertilizer during the last 5 years, and therefore differences in rubber productivity may have an impact on soil nutrient status. To date, no evaluation has been conducted regarding soil fertility and the impact of fertility management on rubber production at this plantation. Therefore, this study was conducted to evaluate soil fertility conditions across different rubber productivity levels as a foundation for improving soil fertility management. Based on this background, this study aims to evaluate the soil fertility status of high and low productivity lands at the Banjarsari Plantation, PT Perkebunan Nusantara I Regional 5. We hypothesized that the high rubber productivity is directly correspond to soil nutrient content, however the high rubber productivity can lead to decrease soil nutrient content if not balanced by proper fertilization.

MATERIALS AND METHODS

Study site: The research was conducted from January to June 2024 at Banjarsari Plantation, PT Perkebunan Nusantara I Regional 5 Jember Regency especially (Figure 1). Geographycally, the site is located at 8°10'51"S 113°35'35"E to 8°11'10"S 113°35'05"E. The average rainfall during the research was 121.33±28.4 mm/month, average air temperature 28.2 ± 0.27 ºC, and average air humidity 79.7 ± 2.13 % (PT Perkebunan Nusantara I Regional 5, 2024). In addition, the site is located in an lowland area with a mean elevation of 45 m and soil type is Regosol and Latosol.

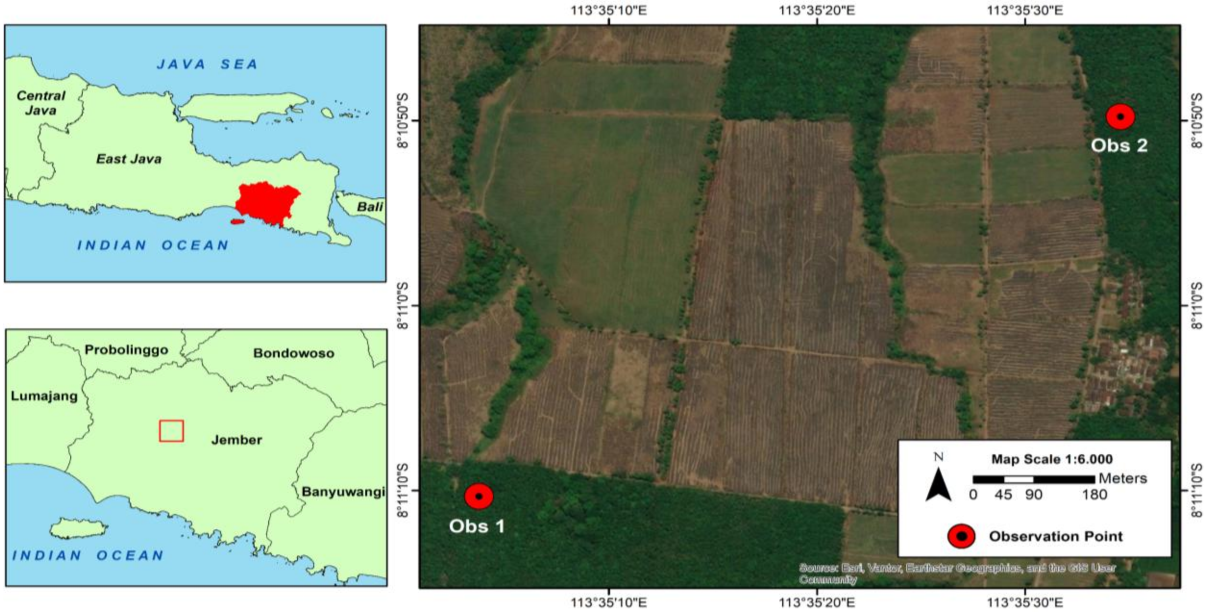

Figure 1. Research Location Map in the PT Perkebunan Nusantara I Regional 5 Jember Regency, Jember East Java, Indonesia

Research design and data collection method: The field research was conducted at the rubber plantation that have a high and low rubber productivity. The high and low rubber productivity was determined from the record of rubber productivity from 2020 to 2022 (Table 2). The land with low rubber productivity has annual production 863 ± 114.18 kg ha^{-1} (≤ 1000 kg ha^{-1}), whereas the anual production in the land with high rubber productivity was 1511.3 ± 139.75 kg ha^{-1} (≥1500 kg ha^{-1}). The low rubber productivity had rubber productivity ≤ 1000 kg/ha, while the high rubber productivity had ≥ 1500 kg/ha. Rubber tree was planted with spacing 6 m x 3 m. In addition, the rubber tree is planted on 2012 and 2013 with clone of PB 260, which has characteristics such as rapid latex metabolism (quick starter), with initial production exceeding 1500 kg ha^{-1} per year and subsequent production reaching 2500-3000 kg ha^{-1}per year. Other characteristics include good growth, strong wind resistance, high resistance to pink disease (*Upasia salmonicolor*), and a positive response to latex stimulants (PT Perkebunan Nusantara XII, 2018). Prior to our study, fertilizer (i.e., NPK fertilizer) and/or soil amendments such as lime (i.e., $CaCO_3$) or dolomite ($CaMg(CO_3)_2$) was not applied in the land with high and low rubber productivity during the last five years.

Table 2. Rubber productivity in the research plot during 2019 to 2023

Year	Area (ha)	Productivity (kg ha^{-1})	
		Low	High
2020	99.31	635	1,239
2021	99.31	966	1,593
2022	99.31	988	1,702

Sample collection: At each the land area with high and low rubber productivity, the research plot was set up at a size 20 m x 20 m, with three replication of each (Fig. 2). The minimum distance between plots was keptat least 500 m. Soil sample was collected at 5 sampling point and two soil depth i.e., at 0-20 cm and 20-40 cm (Fig. 2). At each depth of soil, soil sample from the 5 sampling points in each plot was homogenously mixed due to the plot is homogen (i.e., rubber old, slope, topography, soil type and management), then the soil was air dried, and a representative sample was taken (approximately 200 g) for laboratory analysis.

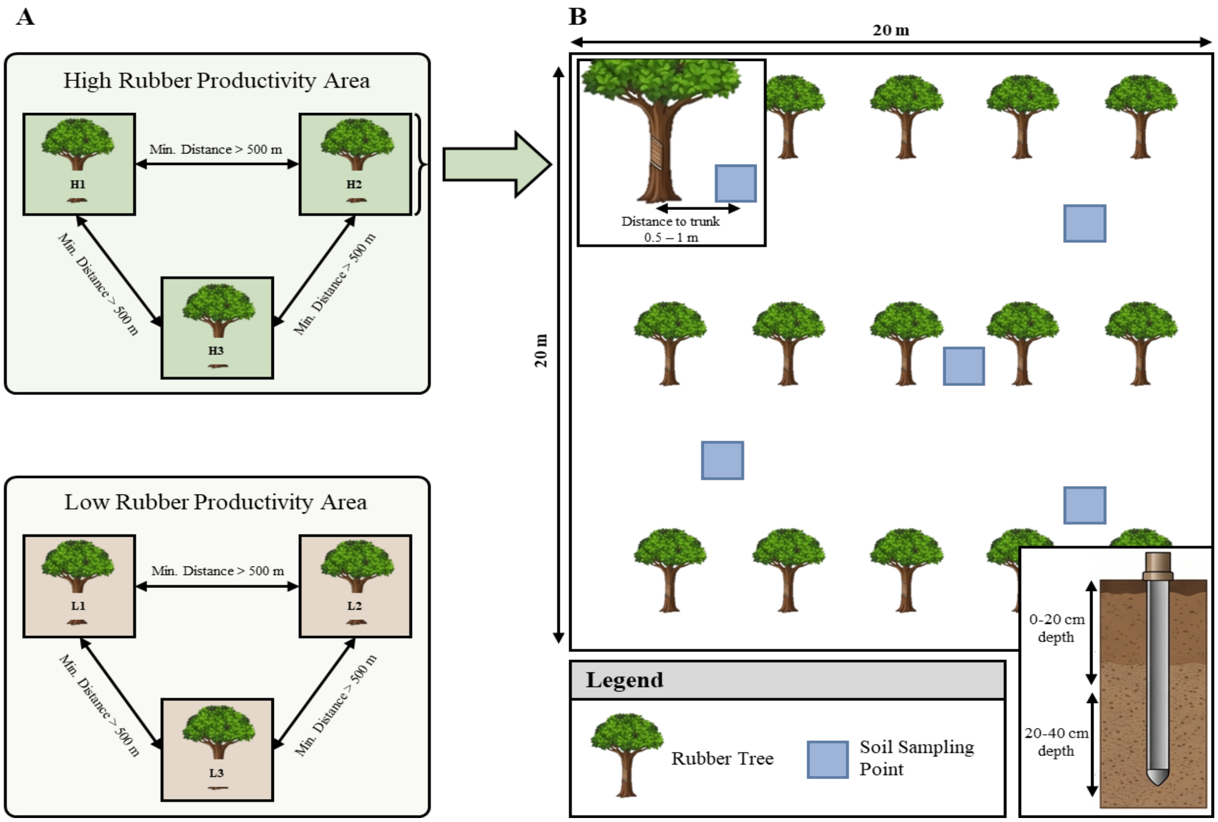

Figure 2. Soil sampling design at each plot

Sample analysis: The laboratory analysis was conducted at the University of Jember/State Polytechnic of Jember and International Cofffee and Cacao Research Institute (ICCRI) Jember, Indonesia. The variable measured including soil organic C, pH, total N, available P, exchangeable K, exchangeable Ca, exchangeable Mg, exchangeable Na, cation exchange capacity (CEC), and base saturation (%). Soil organic C was determined using Walkley-Black method, and total N using Kjeldahl method (Balai Pengujian Standar Instrument Tanah dan Pupuk, 2023). Soil available P was analyzed using spectrophotometry, where soil exchangeable K was analyzed using Ammonium Acetate (NH_4OAc) Extraction method (Balai Pengujian Standar Instrument Tanah dan Pupuk, 2023).

Data analysis methods: Prior to statistical analysis, the data was tested for normality (ShapiroWilk's test). For the not-normal data ($p \leq 0.05$), the data was transformed using logarithmic or square-root to minimize the outlier data and to equalize the variance. To analyze differences of soil chemical properties between the high and low rubber productivity, as well as between the top (0-20 cm) and the sub (20-40 cm) soils we used Linear Mixed Effect Model (Kurniawan et al., 2018) with rubber productivity and soil depth as the fixed effect, whereas the replicate plots as the random effect. The LME used due to this analysis is particularly powerful because soil data is almost never truly independent. While, to analyze the relationship among soil chemical properties and the relationship between soil nutrient characteristics and rubber productivity were conducted using Pearson correlation and Principal Component Analysis (PCA). All statistical analysis was conducted using R version 4.1.0.

RESULTS AND DISCUSSION

Soil organic carbon and nitrogen between low and high rubber productivity: Soil organic C and total nitrogen is mainly affected to rubber productivity. The laboratory analysis showed that soil organic C in the low and rubber productivity ranged from 1.21 % to 4.97 % at 0-20 cm depth of soil and 1.17% to 2.67% at 20-40 cm depth of soil. The organic C in the Banjarsari rubber plantation had high variation in soil organic C content, showed by the amount of soil organic C was from low to very high, especially in the top soil (Balai Pengujian Standar Instrument Tanah dan Pupuk, 2023). While, soil organic C in the sub soil was ranged from low to medium class. In addition, the study detected that soil organic C between the low and the high rubber productivity was comparable (1.79±0.25 % and 2.46±0.56 %; Fig. 3A). Unfortunately, the study was unable detected significant different of soil organic C between the top 20 cm and the 20-40 cm depth of soil (2.46±0.57 % and 1.79±0.22 %; Fig. 3B). This was probably due to the input of organic matter from leaf litter and organic fertilizer. Compared to the soil organic C in the rubber plantation in Jambi – Sumatra, the average soil organic C in the Banjarsari rubber plantation (1.76% - 3.15%) was higher than soil organic C in the smallholder rubber plantation in Jambi – Sumatra (0.90% - 1.56%), reported by Kurniawan *et al*. (2018).

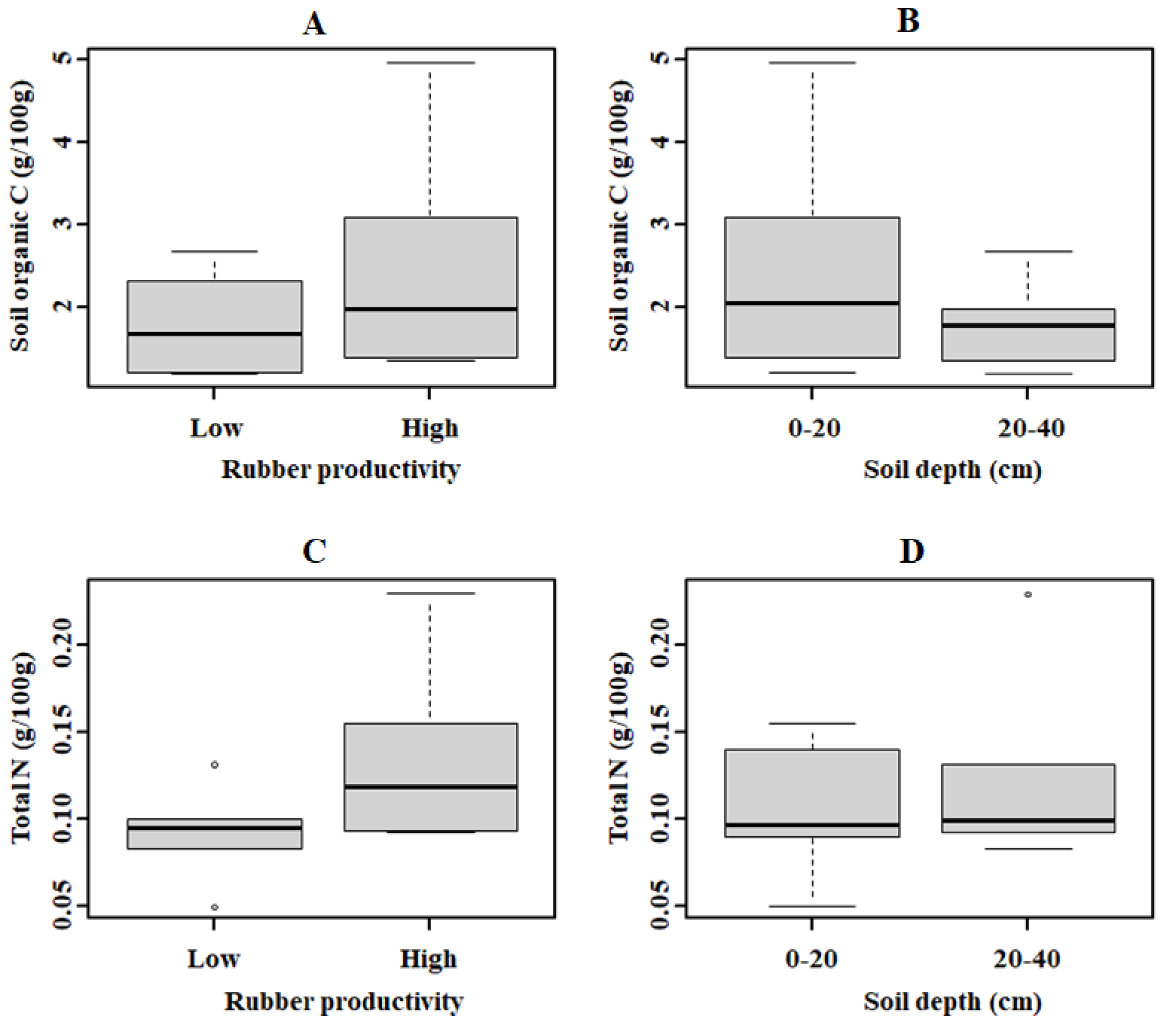

Figure 3. Soil organic carbon (A) and total nitrogen (C) in the low and high rubber productivity, and in the 0-20 cm (B) and 20-40 cm (D) soil depth within Banjarsari rubber plantation, Jember – Indonesia

Total N in the Banjarsari rubber plantation ranged from 0.05% to 0.155% in the top soil (0-20 cm) and 0.08 g/100g – 0.23 g/100g in the sub soil. Statistical analysis showed that total N between the low and high rubber productivity, as well as between the top and the sub soil, were comparable (P = 0.197; Fig. 3C and D). However, the high rubber productivity (0.13 ± 0.02 g N/100g) tend to have 46% higher of total N than those in the low rubber productivity (0.09 ± 0.01 g N/100g). This result indicated that the soil condition in the high rubber productivity is more fertile as compared to the low rubber productivity. In addition, the lower total N in the low rubber productivity as compared to the high rubber productivity was probably due to higher N losses (i.e., leaching, volatilisasi) in the low than in the high rubber productivity. Utami *et al*. (2021) reported that total soil pore at 0-20 cm depth of soil in the rubber plantation was around 50%, which may potentially support nutrient leaching process.

Nitrogen is the primary essential nutrient and play a crucial role in increasing rubber growth and productivity. The previous research reported that the role of nitrogen in the rubber plantation consist of promoting vigorous growth, increasing latex yield and quality, and enhancing the nutritional content of the latex (Jin *et al*., 2024). However, a research by Lopez *et al*. (2025) reported that the increases in application doses of NPK fertilizers did not significantly affected to the growth of isodiametric trunk and rubber yields. Therefore, proper nitrogen fertilization can helps the rubber trees growing faster, reaching tapping age sooner, and maintaining higher productivity.

Soil exchangeable cation between low and high rubber productivity: The study detected a high vation in soil exchangeable base cation (i.e., K, Na, Ca) between the low and high rubber productivity, whereas the soil exchangeable Mg between the low and high rubber productivity was comparable (Fig. 4A-D). Soil in the low rubber productivity had 41% and 11% higher of soil exchangeable K and Ca (1.61 ± 0.10 $cmol_c$/kg and 9.27 ± 0.25 $cmol_c$/kg, respectively) as compared to those in the high rubber productivity (1.14 ± 0.17 $cmol_c$/kg and 8.34 ± 0.29 $cmol_c$/kg) at all soil depth (Fig. 4A and C). In contrast, soil exchangeable Na in the high rubber productivity was 78% higher than those in the low rubber productivity (Figure 4B). Furthermore, soil exchangeable base cations (i.e., K, Na, Ca, Mg) between the top and the sub soil at rubber plantation within Banjarsari rubber plantation was not significant different ($P \geq 0{,}05$; Fig. 4 E-H).

The higher soil exchangeable K and Ca, as well as the lower soil exchangeable Na, in the low than in the high rubber productivity may affected by nutrient uptake by plant. In general, plants absorb more K and Ca than Na because these two nutrients are essential nutrients. Potassium has a positive effect on latex yield and quality, translocation of sugars to the latex-producing vessels (the latex sink), and regulation of stomatal function and maintains turgor pressure in plant cells (Putra *et al*., 2022). While Ca helps to increase the yield of latex by facilitating the uptake of other nutrients like magnesium, root development, and increased latex yield (Putra *et al*., 2022). Therefore, the lower soil exchangeable K and Ca in the high rubber productivity than those in the low rubber productivity inlined with the latex production. This was supported by the measurement on 2024, latex production in the high rubber productivity ranged from 1567 – 2041 kg/ha, whereas in the low rubber productivity was 704 – 1094 kg/ha. Furthermore, the lower K and Ca in the land with high rubber productivity than those in the low rubber productivity may related to fertilization. Field interview with the field workers noted that the study area did not applied fertilizer (e.g., NPKCa) and soil amendment (i.e., lime or dolomite) containing Ca. Therefore, the depletion of soil nutrients through harvesting and the low nutrient inputs (K, Ca) from bulk precipitation have led to a decrease in soil exchangeable K and Ca. This result inlined with our hypothesis that the high rubber productivity can lead to decrease soil nutrient content (i.e., K and Ca) if not balanced by proper fertilization.

Compared to the previous research, soil exchangeable K, Ca, and Mg (1.12 – 1.62 cmol K/kg, 7.91 – 9.34 cmol Ca/kg, and 2.93 – 3.43 cmol Mg/kg) in our study area were higher than those reported by Yasin *et al*. (2010) who measured soil exchangeable cations at the 10th and 15th age of rubber plantation in Ultisol – Dhamasraya, West Sumatera (0.39 – 0.41 cmol K kg^{-1}, 0.48 – 0.68 cmol Ca/kg, and 0.13 – 0.16 cmol Mg kg^{-1}). This is showed that soil in the Banjarsari rubber plantation area is more fertile as compared to soil in the rubber plantation in the Dhamasraya West Sumatera, probably due to soil in the Banjarsari rubber plantation was younger than soil in the study area of Yasin *et al*. (2010). In addition, the Pearson correlation test showed strong relationship between soil exchangeable Mg and base saturation (Table 3).

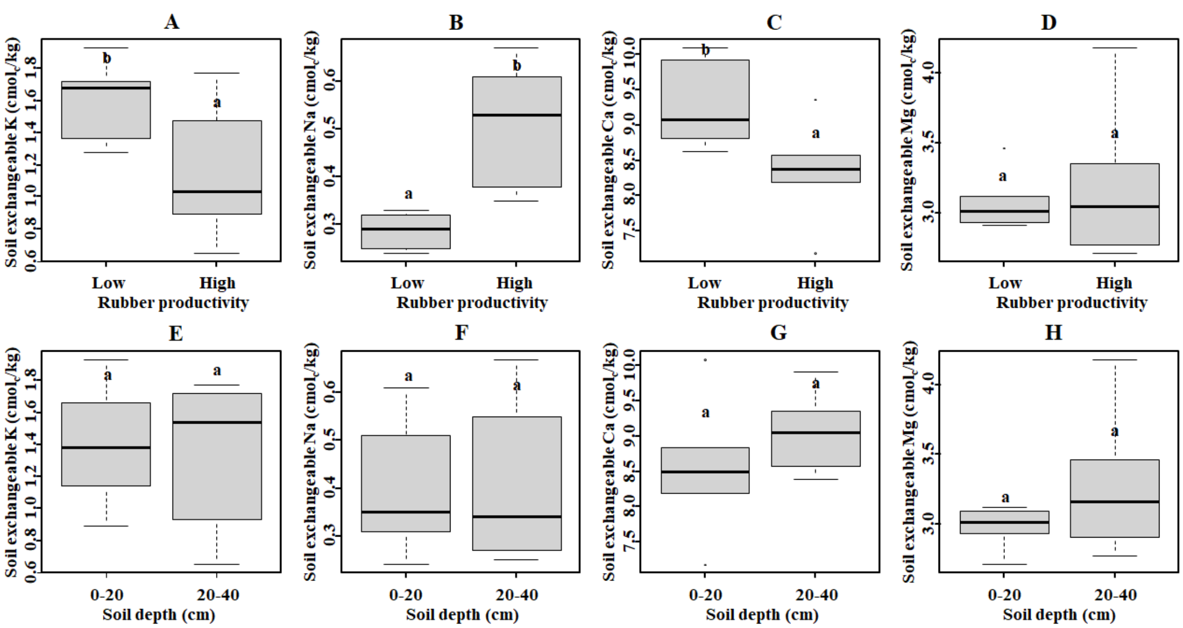

Figure 4. Soil exchangeable base cations (K, Na, Ca, Mg) between the low and high rubber productivity (A-D) at all soil depth (E-H) in the Banjarsari rubber plantation, Jember – Indonesia

Soil available P and potential soil fertility between the low and high rubber productivity: The average of soil available P between the low and high rubber productivity area ranged from 4.68 – 14.72 mg kg^{-1}, categorized as very low to low soil available P (Fig. 5; Balai Pengujian Standar Instrumen Tanah dan Pupuk, 2023). At all soil depth, the study detected unsignificant different of soil available P between the area with low and high rubber productivity, as well as between the top and the sub soil ($P \geq 0.05$). However, the area with low rubber productivity (11.25±3.42 mg P kg^{-1}) tend to have 90% higher soil available P as compared to the area with high rubber productivity (5.91±2.06 mg P kg^{-1}). This result inlined with soil exchangeable K and Ca where the decreases in soil available in the high rubber productivity due to nutrient depletion through harvest and the low input (i.e., bulk precipitation). P is one of crucial element for supporting rubber tree growth and a key factor for optimizing productivity, especially under monoculture conditions (Hemati et al., 2020). Kurniawan et al. (2017) reported that P lost in the rubber plantation through harvest export and leaching losses was ranged from 2.83 – 4.75 kg P/ha. While, annual input of total P from bulk precipitation ranged from 0,4 – 0,8 kg ha^{-1} yr^{-1} (Kurniawan et al., 2018). Thus, the land with high rubber productivity without P fertilizer application, the lost of P through harvest export lead to decrease in the availability of P in the soil. This study suggested that P fertilizer is needed in the area with high rubber productivity to maintain soil available P level and rubber productivity.

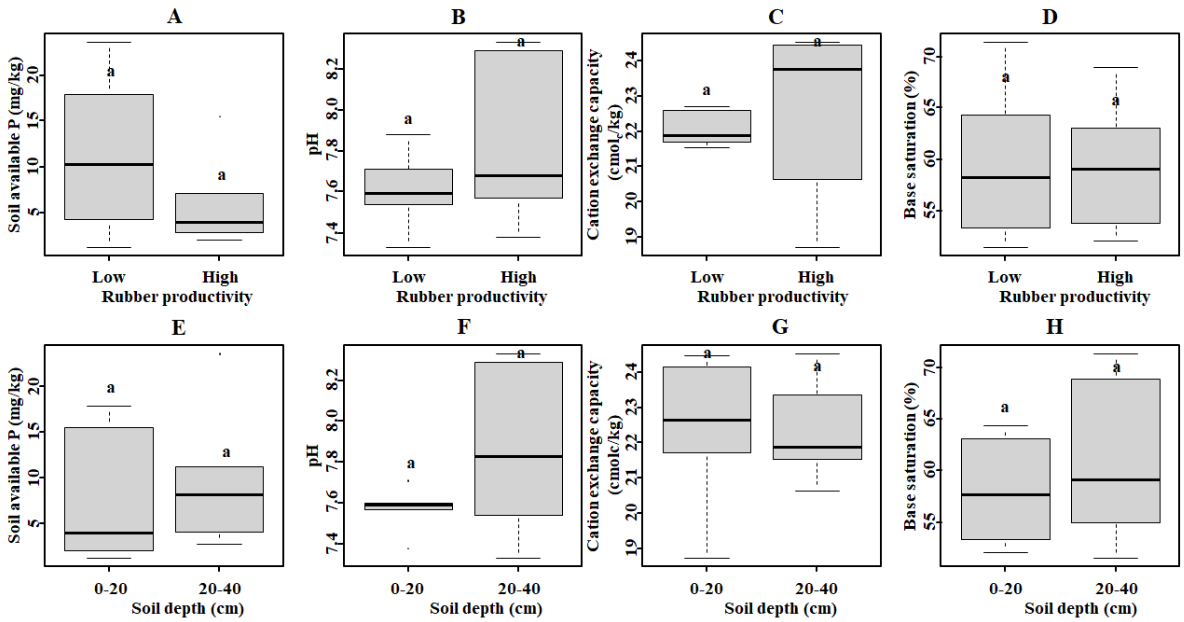

Figure 5. Soil available P, soil pH, CEC, and base saturation between the low and high rubber productivity (A-D) in the top and sub soil (E-H)

Soil in the rubber plantation within Banjarsari plantation PT Perkebunan Nusantara I Regional 5 Jember Regency, Indonesia, classified as neutral to slightly alkaline with pH value ranged from 7.33 to 8.33 (Fig. 5). This was due to the soil contain a high amount of base cations (i.e. K, Mg; Fig. 4), supported by the high base saturation (base saturation ranged from 51.46 % - 71.39%; Fig. 5). When the base saturation is high, it means that base cations are abundant and replace acid cations (such as Al^{3+} and H^{+}) in soil adsorption complexes, resulting the soil pH to become higher. In addition, the study detected unsignificant different of soil pH, cation exchange capacity (CEC) and base saturation between the low and high rubber productivity at 0-20 cm and 20-40 cm depth of soil (Fig. 5 B-D). In addition, soil pH, CEC, and base saturation between 0-20 cm and 20-40 cm depth of soil was also comparable (Fig. 5 E-H). In addition, the Pearson correlation test (Table 3) showed the strong positive correlation (r = 0.75, r table = 0.497, p value = 0.005) between base saturation and soil exchangeable Mg, indicated that the low variation in base saturation between the area with high and low rubber productivity (59.34±6.39 % and 59.50±7.66 %, respectively). Furthermore, the base saturation in the study area is classified as medium to high (Balai Pengujian Standar Instrumen Tanah dan Pupuk, 2023), indicated that the soil inherently possess a greater capacity for cation retention, which is crucial for nutrient availability in rubber plantations (Allen et al., 2015).

The relationship between soil chemical characteristics and latex production: Latex production in 2024 was ranged from 714– 2041 kg ha^{-1} (Table 2). The area of high rubber productivity had 91% higher of latex production (1831.67 ± 139.60 kg ha^{-1}) as compared to the area of low rubber productivity (957.00 ± 121.83 kg ha^{-1}). Latex production is affected by internal (i.e., clone, age, and plant physiology) and external (i.e., climate, soil, tapping practice). Related to soil nutrient, latex production had positive correlation to soil exchangeable Na (Pearson correlation, r = 0.82, r table 5% = 0.497, p value = 0.001; Table 3). This result shown that functional elements such as Na plays an important role on stomatal regulation and increases photosynthesis performance in rubber trees (Battie-Laclau *et al*., 2016; Mateus *et al*., 2021) In contrast, latex production tend to have negative correlation with soil exchangeable Ca and soil available P (Table 3, p value = 0.11). In addition, soil soil total N showed the trend of positive correlation to latex production (r = 0.45, p-value = 0.14, Table 3). The study was unable to detected significant correlation between cation exchange capacity, base saturation, soil pH, and soil organic C with latex production (Table 3). This result similar to Putra *et al*. (2022) who reported that soil exchangeable cations (i.e., K, Ca, Mg) was insignificant correlated to latex production (r = -0.18 to 0.11). Further, the growth and production of rubber is mainly affected by soil and climate condition. Therefore, the low soil fertility due to low organic matter content, soil pH, and availability of potassium (K) and phosphorus (P) are limiting factors for rubber growth and production (Ardika and Sanchez, 2025).

Table 3. Matrix Pearson coefficient correlation among soil chemical properties and rubber productivity in the the Banjarsari rubber plantation, Jember – Indonesia

Parameter	**Soil org. C (g/100 g)**	**Total N (g/100 g)**	**Soil exc. K ($cmol_c$/kg)**	**Soil exc. Na ($cmol_c$/kg)**	**Soil exc. Ca ($cmol_c$/kg)**	**Soil exc. Mg ($cmol_c$/kg)**	**Soil pH**	**Soil available P (mg/kg)**	**CEC ($cmol_c$/kg)**	**Base saturation (%)**	**Rubber productivity (kg/ha)**
Soil org. C (g/100g)	1	0.32	-0.06	0.22	-0.46	-0.09	-0.45	0.13	-0.49	0.13	0.20
Total N (g/100g)	0.32	1	-0.58*	0.10	-0.40	-0.42	0.33	-0.04	-0.004	-0.27	0.45
Soil exc. K ($cmol_c$/kg)	-0.06	-0.58*	1	-0.19	0.45	-0.06	-0.29	0.19	0.08	0.09	-0.36
Soil exc. Na ($cmol_c$/kg)	0.22	0.10	-0.19	1	-0.20	0.24	0.30	-0.44	0.44	-0.007	0.82**
Soil exc. Ca ($cmol_c$/kg)	-0.46	-0.40	0.45	-0.20	1	0.14	0.13	-0.18	0.29	0.31	-0.48
Soil exc. Mg ($cmol_c$/kg)	-0.09	-0.42	-0.06	0.24	0.14	1	0.06	-0.05	-0.37	0.75**	0.0004
Soil pH	-0.45	0.33	-0.29	0.30	0.13	0.06	1	-0.25	0.46	-0.03	0.36
Soil available P (mg/kg)	0.13	-0.04	0.19	-0.44	-0.18	-0.05	-0.25	1	-0.60*	-0.25	-0.48
CEC ($cmol_c$/kg)	-0.49	-0.004	0.08	0.44	0.29	-0.37	0.46	-0.60*	1	-0.40	0.42
Base saturation (%)	0.13	-0.27	0.09	-0.007	0.31	0.75**	-0.03	-0.25	-0.40	1	-0.11
Rubber productivity (kg/ha)	0.20	0.45	-0.36	0.82**	-0.48	0.0004	0.36	-0.48	0.42	-0.11	1

= significant different at $p \leq 0.05$; ** = significant different at $p \leq 0.01$; r table 5% = 0.497

The principal component analysis (PCA) performed using fixed factor-mean data (Table 4; Figure 6A) demonstrated a strong multivariate structure among soil chemical properties and rubber productivity variables. PC1 exhibited an eigenvalue of 8.482 and explained 57.83% of the total variance, while PC2 showed an eigenvalue of 5.086 and accounted for 34.67% of the variance. Collectively, the first two principal components explained 92.51% of the cumulative variance, indicating that the majority of variability in the fixed factor (i.e., low and high rubber productivity, soil depth) dataset could be effectively represented within a two-dimensional ordination space. The high cumulative variance suggests that the treatment-based PCA successfully reduced dataset dimensionality while preserving most of the information contained within the original variables. This strong separation pattern observed in Figure 6A reflects the reduced within-the land with difference rubber productivity and soil depth variability resulting from replicate averaging, thereby emphasizing the dominant differences among sampling site. Variables with similar vector orientations in the PCA biplot likely exhibited positive correlations, whereas variables positioned in opposite directions reflected contrasting responses among treatments. The high explanatory power of PC1 and PC2 indicates that soil nutrient content and rubber productivity responses were strongly structured across the treatment gradients.

Table 4. Eigenvalues, explained variance, and cumulative variance of principal components derived from soil chemical properties and rubber productivity variables.

Principal Component	Eigenvalue	Variance Explained (%)	Cumulative Variance (%)
PC1	8.482	57.832	57.832
PC2	5.086	34.674	92.506
PC3	1.099	7.494	100.000
PC4	0.000	0.000	100.000

In contrast, the PCA based on all individual observations without averaging replication (Table 5; Figure 6B) revealed a more moderate and realistic multivariate structure. PC1 explained 29.30% of the total variance with an eigenvalue of 3.516, while PC2 contributed 22.61% with an eigenvalue of 2.713. Together, the first two components accounted for 51.91% of the cumulative variance, substantially lower than the treatment-mean PCA (Table 4, Figure 6A). Additional variability was distributed across higher principal components, particularly PC3 (18.79%) and PC4 (11.50%), indicating the presence of considerable heterogeneity among individual soil samples / replication. This pattern suggests that soil chemical properties and rubber productivity were influenced by multiple interacting factors rather than a single dominant gradient. The lower variance explained in Figure 6B reflects the preservation of natural biological and environmental variability among replicates, which is commonly observed in soil ecological datasets. Consequently, the individual-observation PCA provides a more conservative yet statistically robust representation of the relationships among soil properties and productivity variables. The contrast between Figures 6A and 6B demonstrates how replicate averaging can artificially strengthen apparent multivariate separation by minimizing within-group variation, whereas analysis using all independent observations preserves the true complexity and variability of the soil system.

Table 5. Eigenvalues, explained variance, and cumulative variance of principal components derived from soil chemical properties and rubber productivity variables.

Principal Component	Eigenvalue	Variance Explained (%)	Cumulative Variance (%)
PC1	3.516	29.296	29.296
PC2	2.713	22.610	51.906
PC3	2.255	18.793	70.699
PC4	1.380	11.502	82.202
PC5	0.884	7.371	89.572
PC6	0.665	5.546	95.118
PC7	0.344	2.866	97.984
PC8	0.175	1.455	99.438
PC9	0.054	0.451	99.889
PC10	0.012	0.099	99.988
PC11	0.001	0.012	100.000

Overall, PCA result showed soil exchangeable Na, total N, cation exchange capacity (CEC), and soil organic C affected to latex production. Gashua *et al*. (2023) stated that organic nitrogen sources often promote healthier root systems in crops, which are essential for efficient nutrient and water uptake. While, Ginting and Astuti (2017) reported that application of macro and micro nutrients on the rubber rods enhance the production of latex and dry rubber content value.

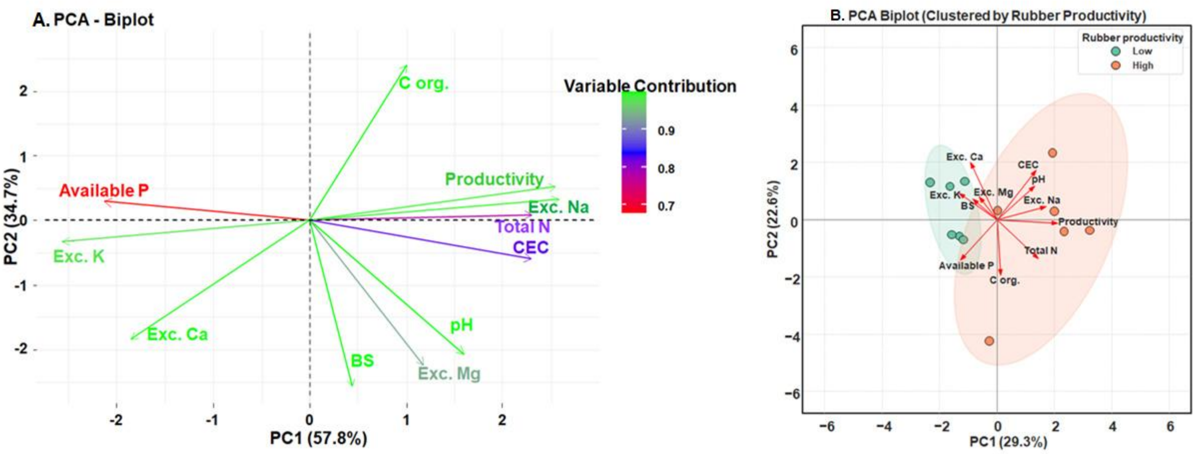

Figure 6. Principal component analysis of the relationship between soil chemical characteristics and latex production in the low and high rubber productivity (a) and clustering based on the low and high rubber productivity (b). Note: N = 12, C.org = soil organic C, Productivity = latex production, Exc. K, Na, Ca, Mg = soil exchangeable K, Na, Ca, Mg, Total N = soil total N, Available P = soil available P, BS = base saturation, CEC = cation exchange capacity.

Conclusion: The study highlighted that soil chemical properties (i.e., total N, soil exchangeable K, Na, and Ca) was significantly different between in the high and low productivity areas of Banjarsari Rubber Plantation, PT Perkebunan Nusantara I Regional 5. Differences in soil chemical properties affect to the rubber production, supported by the relationship between rubber production and soil exchangeable cations (i.e., Na). In addition, this research detected the increases of nutrient concentration in the deeper layer such as N and Ca, indicated nutrient leaching losses. Thus, in the areas with low rubber productivity, fertilization should be carried out properly to increase rubber yield, particularly by combining organic and inorganic fertilizers such as NP fertilizers. While, the decline in essential macronutrient content (i.e., P, K, and Ca) in the high-productivity rubber plantations underscores the urgent need for proper application of NPKCa fertilizers to maintain soil nutrient content and rubber productivity.

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