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IMPROVING RUBBER PRODUCTION AND TAPPING PANEL DRYNESS IN *Hevea* TREE USING ORGANIC FERTILISER AND MICRONUTRIENTS

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Abstract: Tapping Panel Dryness (TPD) is a condition that affects latex-producing cells, leading to reduced latex flow upon cutting the tree bark. Here, a comparative analysis was conducted to evaluate soil nutrient levels beneath TPD-affected trees and healthy trees. The findings revealed that Calcium (Ca) and Magnesium (Mg) levels were 1.76 and 1.38 times lower, respectively, in TPD-affected trees compared to healthy trees. The application of organic fertiliser on rubber farms significantly improved soil conditions, especially Mg content. Moreover, the use of organic fertiliser significantly enhanced the Dried Rubber Content (DRC) and rubber dry weight compared to untreated soil. Additionally, organic fertiliser mixed with various micronutrients was applied to the soil under the TPD-affected trees. The finding demonstrated that applying Murashige and Skoog (MS) medium to the bark, combined with organic fertiliser, substantially reduced the length of cut dryness in TPD-affected trees from 77.6% to 13%. Furthermore, TPD-affected trees treated with organic fertiliser and 0.5 kg of nine chemical Micronutrient Granules (MGs) exhibited the highest latex output compared to other treatments. This combination of organic fertiliser and chemical MGs provides a balanced nutrient supply, promoting rubber tree growth and optimising latex production.

Keywords: Soil nutrients, formular fertilisation, socioeconomic, latex, dry cut.

Introduction

Rubber trees (*Hevea brasiliensis* wild ex. A. Juess Arg.) are cultivated in tropical regions for latex production, covering over 10 million hectares (FAO, 2018). Most of the world's natural rubber is produced in Asia, with Thailand, Indonesia, and Malaysia accounting for 97% of production (Fox & Castella, 2013; Ratnasingam *et al*., 2015). In 2023, Thailand alone produced 4.7 million metric tonnes of natural rubber, representing 36% of global production, making it the world's largest rubber producer (Statista, 2024). Notably, most natural rubber is sourced from smallholder farmers with plantations of less than 8 hectares, predominantly focusing on *Hevea* mono-cropping (Jongrungrot *et al*., 2014). Smallholder farmers cultivating rubber trees must carefully manage resources like fertilisers, water, and pesticides. Fertilisers play a crucial role in promoting healthy rubber tree growth and maximising latex yields, making their effective use essential to minimise waste and avoid unnecessary expenses (Baharom & Razali, 2023). During periods of low rubber prices and increasing fertiliser expenses, farmers often adjust their fertiliser management strategies such as reducing chemical fertilisers, switching to lower-cost brands, or adopting organic fertilisers (Kullawong *et al*., 2020).

For optimal *Hevea* tree yields, effective irrigation and fertiliser application systems are essential. While irrigation promotes rubber girth growth (Chandrasekhar *et al*., 2005), non-irrigated treatments lead to higher incidences of Tapping Panel Dryness (TPD), a physiological disorder affecting the laticifer cells in the bark and limiting crop productivity in high-yielding clones (Mak *et al*., 2008; Nayanakantha, 2021). TPD is caused by the accumulation of Reactive Oxygen Species (ROS) due to over-exploitation during latex harvesting (Tistama *et al*., 2019). Although both *Hevea* monoculture and intercropping systems are susceptible to TPD, smallholder farmers often struggle to select and grow TPD-free trees. Several strategies have been suggested to reduce TPD severity, including the use of micronutrient solutions and treatments with Shrimp Waste-enriched Compost Extract (SWCE) (Suwandi *et al*., 2018; Fipriani *et al*., 2019). However, these approaches require frequent interventions and can be costly, potentially resulting in a year of lost latex production. Despite ongoing efforts to understand the causes and prevention of TPD in rubber trees, small-scale rubber farmers, including those practicing intercropping, still encounter these challenges.

This study focuses on soil nutrient analysis under healthy and TPD-affected *Hevea* trees, aiming to develop organic fertiliser and utilise micronutrients to treat TPD, thereby reducing production costs for smallholder rubber farmers. Organic fertilisers supply essential plant nutrients and energy sources for soil microbes, improving soil quality and productivity (Kumar *et al*., 2017). Additionally, the research analyses socio-demographic factors linked to TPD syndrome to offer practical solutions for smallholder rubber farmers. Correspondingly, the findings from this study are expected to contribute to the development of strategies that enhance rubber yields while mitigating TPD in *Hevea* trees.

Materials and Methods

Experimental Design and Site Description

This study follows a descriptive and comparative design, comparing two groups of rubber farmers. It focuses on socio-demographic factors, farming practices, and the impact of TPD. The research was conducted on rubber smallholder farms in Tamote District, Phatthalung Province, Thailand (Figure 1). The sampling method employed was purposive sampling, which selected rubber

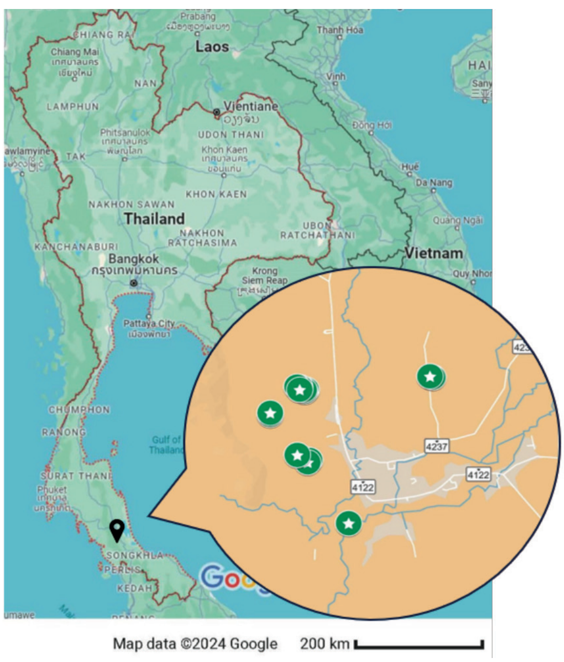


Figure 1: Soil sampling location in the study areas in Tamote Districts, Phatthalung Province, Southern Thailand. The zoomed-in map shows the soil sampling sites, indicated by green dots

Source: Google Maps (2024)

farmers from specific subdistricts where rubber intercropping criteria were followed and TPD was prevalent. The local climate is influenced by the Asian monsoon, resulting in two district seasons: A rainy season from September to January and a dry season from February to July. The region experiences an average annual temperature of 28°C with a relative humidity of 73%. Wind speeds range from 1 to 2 m/s and the evaporation rate varies between 3.3 to 55 mm/day. The annual rainfall averages 2,038 mm and the predominant soil type is sandy loam (Tamote Municipality, 2023).

Sampling and Sample Size

The sample consisted of 100 rubber smallholder farmers registered with the Rubber Authority of Thailand, Bang Kaeo Branch Office. Among them, 62 were members of a rubber intercrop group while 28 were farmers from areas with rubber plantations near the rubber intercrop group. These farmers were selected from two subdistricts: The Tamote Subdistrict and the Khlong Yai Subdistrict. This specific area was selected since the rubber farms adhered to rubber intercropping criteria and were affected by TPD. Socio-demographic data was collected using a semi-structured questionnaire (Human Ethic CoA No. TSU2021-026) through face-to-face interviews to gain a comprehensive understanding of the farmer's practices, following the methodology of Somboonsuke *et al*. (2009).

Soil Sampling

A survey was conducted on fifteen rubber farms belonging to the rubber intercrop group. The study involved collecting soil samples from trees affected by TPD as well as from healthy trees. For each rubber farm, soil samples were collected from ten healthy trees and ten TPD-affected trees. Both pre-and post-application soil samples of organic fertiliser were obtained. Soil samples were collected at three points around each tree, with each sub-plot contributing ten samples from holes at a depth of 0 to 30 cm. These samples were combined to create composite samples, which were then subjected to analysis.

The analysis followed the standard method described by Narwal *et al*. (2004). Soil pH was determined using a 1:2 ratio of soil to water, measured with a pH metre. Organic matter content was assessed using the Walkley and Black method (1934). Available Phosphorus (P) was extracted using the Bray II method and detected via Ultraviolet-Visible spectroscopy (UV-Vis) spectroscopy. Exchangeable Potassium (K), Calcium (Ca), Magnesium (Mg), Iron (Fe), and Zinc (Zn) levels were extracted and measured using an atomic absorption flame spectrophotometer. The study prioritised the evaluation of macronutrients (N, P, K, Ca, Mg) and essential micronutrients (Fe, Zn), which are critical for soil fertility and plant growth. These nutrients are typically the most impactful in determining soil and plant health. At the same time, soil Electrical Conductivity (EC) was measured using a 1:10 soil-to-water ratio and detected with an EC metre. Total Nitrogen (N) was assessed using the Potassium Chloride (KCl) soil extraction method.

Organic Fertiliser and Micronutrient Production

The material sources used in the study included chicken manure, cow manure, cayenne shells, fish meal, sawdust, rice husk ash, rice bran, rock phosphate, and dolomite. The composition of the organic fertiliser consisted of various components blended as follows: Chicken manure (25%), cow manure (10%), cayenned shells (5%), fish meal (10%), sawdust (20%), rice husk ash (10%), rice bran (5%), rock phosphate (8%), and dolomite (1%). To initiate fermentation, the enriched compost was mixed with soil microbial fermentation agents (6%). The feedstock materials for the organic fertilisers were collected from various sites in Phatthalung Province, Thailand, including a chicken farm, cow farm, rubber wood processing factory, a rice mill, and an agricultural cooperative. The mixture was then left undisturbed at room temperature for 30 days. During this period, the temperature and pH were monitored while the analysis of plant nutrients was conducted (Table 1).

Regarding the micronutrient solution, the Murashige and Skoog (MS) media solution (Murashige and Skoog, 1962) was prepared using the stock B-D method, as described by Puad and Wai (2016). The MS solution was diluted 1:1 (v/v) before application. The chemical MG mixture contained the following elements: Magnesium Oxide (MgO), Calcium Oxide (CaO), Sulphur (S), Fe, Manganese (Mn), Copper (Cu), Zn, Boron (B), and Molybdenum (Mo), with the following concentrations in fertiliser: 300, 30, 45, 1, 1, 0.5, 0.02, and 0.02 mg/kg, respectively, following the result from Suchartgul *et al*. (2012).

Effect of Organic Fertiliser on Rubber Yield and TPD

The research utilised *Hevea brasiliensis* (RRIM600 clone), which was planted in 2000 and arranged in a 7x3 spacing pattern. The rubber plantation chosen for this experiment contained both healthy trees and those affected by TPD (Figure 2). Various data were collected before and after applying organic fertiliser, including latex yields, the number of TPD-affected *Hevea* trees, and soil properties. Accordingly, treatment of healthy and TPD-affected trees was applied once every six months, with a dosage of 6,250 kg/ha/time, following the results of Hytönen *et al*. (2019). The tapping of *Hevea* trees followed a half-spiral cut (S/2) on two days of tapping followed one day of rest (2d/3) system, which involved tapping every three days with a length equivalent to half a spiral of the stem.

Organic Fertiliser and Micronutrients on TPD Hevea Trees

This research utilised *Hevea* clone RRIM600, which was planted in 2001 with a spacing of 7x3 metres. The experimental design employed a randomised block design with 20 replications for each treatment. Trees affected by TPD were selected by tapping the panel with a taping knife. Tapping of the *Hevea* trees followed an S/2 2d/3 system, where they were tapped every three days using a half spiral length of the stem. The applied method of Nanthanuwat *et al*. (2016) involved bark treatment with Murashige and Skooge (1962), which significantly reduced tapping cut dryness and increased latex yields, indicating recovery from the disorder ($p < 0.05$). When MS was applied to the bark and organic fertiliser on the soil, 100% of partially affected TPD *Hevea* trees recovered in two months. While a tree suffering from TPD cannot be

Table 1: The method for analysing the chemical components of organic fertiliser samples

No.	Parameters	Methodologies	References
1	Moisture content	Oven-drying method	The National Institute of Agro-environmental science (1987)
2	pH, EC	pH and EC were determined by pH metre and EC metre	
3	Total Organic Matter (OM), total Organic Carbon (OC), and C/N ratio	Walkley and Black method	Walkley and Black (1934)
4	Total N	Kjeldahl method	Horwitz (2000)
5	Total P	Spectrophotometric Molybdovanadophosphate method	Horwitz and Latimer (2005)
6	Total K	Flame photometric method	Olsen and Sommer (1982)
7	Ca, Mg, Na, S, Fe, Mn, Cu, Zn	Atomic absorption spectrophotometer	Bascomb (1964)
8	As, Cd, Pb, Hg, Cu, Cr	Method 3051 detected by ICP-OES	In-house method based on US EPA (1994)

effectively treated with only NPK fertilisers, no experiments have analysed the comparison of soil nutrients between trees exhibiting dry bark symptoms. Furthermore, organic fertilisers have not been utilised based on soil analysis from trees exhibiting TPD symptoms.

In each treatment, the outer layers of bark were scraped off to a depth of 30 cm below the tapping panel. All TPD-affected *Hevea* trees in the study exhibited no brown colour or bark necrosis. The adoption of the MG instead of MS influenced the level of TPD in *Hevea* trees, as well as the yield of latex (both volume and dry weight) and the DRC. The TPD-affected trees used in the trial had latex flow ranging from 1% to 100% of the tapping panel and received monthly fertiliser applications. The experiment comprised four treatments as follows: T1 (control): TPD-affected trees with MS applied to the bark, 10 kg of organic fertiliser, and 2,000 ml of MS on the soil, T2: TPD-affected trees with 10 kg of organic fertiliser and 100 g of MG, T3: TPD-affected trees with 10 kg of organic fertiliser and 500 g of MG, and T4: TPD-affected trees with 10 kg of organic fertiliser and 1,000 g of MG. The treated trees received fertiliser applications once a month while water and MS were applied every 15 days. Tapping of the trees occurred using a S/2 2d/3 system.

The fresh latex volume per replication for each treatment was measured daily. The dry rubber content of the latex from each treatment was determined monthly to calculate the yield in grams of dry rubber per tree. Meanwhile, the Dry Cut Length (DCL) was measured monthly to analyse the TPD level of the trees. Immediately after tapping, the dryness of the tapping cut was assessed as a percentage of the DCL in relation to the total length of the tapping cut.

Statistical Analysis

Data analysis involved descriptive statistical methods to summarise the collected data, including percentages and frequencies for categorical data. A paired-sample t-test was utilised to compare the mean differences in soil characteristics after confirming normal distribution and homogeneity of variance. All statistical tests were performed at a significant level of 5%. The data analysis was conducted using Statistical Package for Social Sciences (SPSS) (IBM SPSS statistics 26) software.

The latex yield data were subjected to a t-test with the significance level set at $p < 0.05$ to compare the effects of organic fertiliser application before and after. The experimental design employed a randomised block design and the means were further examined using Duncan's Multiple Range Test (DMRT) analysis. The significant level for evaluating the results was set at $p < 0.05$.

Results and Discussion

Socio-demographic

The socio-demographic characteristics of rubber smallholder farmers, who were members of RAOT Phatthalung Province, Thailand are presented in Table 2. Most households have one to four members and one to four labourers. These farmers had household incomes ranging from USD297 to USD870 per month, with 55% of the group falling within this range. Their monthly household expenses were typically below USD297, representing 58% of their income. Additionally, around 32% of these farmers had incurred debts ranging from USD2,901 to USD14,500 per household while 52% had no debts.

On average, each household cultivated rubber on a land area of 0.16 ha to 1.6 ha. The number of rubber plantations tapped per household was less than 1.6 ha. These farmers boasted extensive experience in rubber farming, ranging from 10 to 20 years, with 47% acquiring their knowledge and skills through learning and guidance from their parents and elderly members. Within the community, the most commonly grown rubber variety was RRIM600, accounting for 74% of plantations. The tapping system employed followed the pattern of S/3 3d/4. Fertilisers were applied once a year, with the majority (62%) using chemical fertilisers.

Table 2: Socioeconomic profile of the farmers and characteristics of rubber farming in upstream Phatthalung province, Thailand

Characteristics	Categories	Percentage (N = 100)
Member of household	1 - 4 people 5 - 8 people	75 25
Labour in household	1 - 4 people 5 - 8 people	96 4
Household income (USD per month)	< 290 291 - 870 871 - 1,740 1,741 - 2,610	41 55 3 1
Household expense (USD per month)	< 290 291 - 870 871 and above	58 40 2
Household debt (USD per household)	0 < 2,900 2,901 - 14,500 14,501 - 29,000 29,001 - 43,500	52 10 32 4 2
Rubber plantation area (Hectare per household)	0.16 - 1.6 1.7 - 3.2 3.3 - 4.8 4.9 - 6.4 6.5 - 8.0	62 27 7 3 1
Rubber tapping area (Hectare per household)	0.16 - 1.6 1.7 - 3.2 3.3 - 4.8 4.9 - 6.4	49 41 7 3
Experience in rubber farming (Years)	< 10 years 10 - 20 years 21 - 40 years 41 - 60 years	8 47 39 6
Hevea clone	RRIM600 RRIT251 BPM24 PB235	74 19 6 1
Tapping system	1/3S 3d/4 1/3S 2d/3 1/3S d/2	72 21 7
Fertiliser application	Chemical (time per year: 1, 2, 3, 4) Chemical + Organic (time per year: 1, 2)	80 (62, 15, 1, 2) 20 (19, 1)

Meanwhile, ethephon usage was minimal, covering only 4% of the total area.

Soil Chemical Properties

Soil samples were collected from rubber trees affected by TPD and healthy trees within the rubber plantation, and their chemical properties were examined. The results revealed a statistically significant decrease ($p < 0.05$) in Ca and Mg levels in the soil samples obtained from TPD-affected trees compared to those from healthy trees. However, no statistical differences were reported for other parameters, indicating that TPD in rubber trees could potentially be attributed to a deficiency in Ca and Mg. Furthermore, the TPD-affected trees exhibited 1.76 and 1.38 times lower concentrations of Ca and Mg, respectively, compared to the healthy trees (Table 3). This is consistent with reports that TPD incidence is influenced by various factors, such as a decrease in latex thiol, inorganic P, pH value, and soil compaction (Nandris *et al*., 2004), but not by Ca and Mg levels.

The occurrence of TPD involves the activation of multiple genes associated with processes like ROS metabolism, programmed cell death, rubber biosynthesis, and responses to ethylene, jasmonate, and wounding (tapping) (Putranto *et al*., 2015). Interviews with small rubber farmers revealed that most of them use ethylene during regular tapping (4%) and only apply ethylene when the rubber tree reaches the stage of being felled for new planting, as indicated in Table 2. Regarding soil compaction, the soil composition was determined to be sandy loam, consisting of 73.75% sand, 15.33% silt, and 10.92% clay. In addition, sandy loam soils are capable of quickly draining excess water but cannot hold significant amounts of water or nutrients for plants. However, plants cultivated in sandy loam soil require more frequent irrigation and fertilisation compared to those grown in soils with a higher clay and silt concentration. Due to their limited micronutrient content, sandy loam soils often necessitate supplemental fertilisation to ensure optimal plant growth and health (Javeed *et al*., 2019).

This result aligns with the data collected from interviews with farmers in the area, which indicated that most farmers fertilise their crops annually, primarily using chemical fertilisers (80%) containing only the essential nutrients N, P, and K and apply fertiliser almost once a year (62%). The optimum ranges for P, K, Ca, S, Fe, Cu, Zn, and B concentrations in soil were 10 to 20, 40 to 80, 50 to 600, 25 to 35, 30 to 90, 0.5 to 1.5, and 0.3 to 0.7 mg/kg, respectively (Suchartgul *et al*., 2012). At the same time, one tonne of rubber tree biomass (including leaves, stumps, and roots) contained an average of 2.4 kg N, 0.2 kg P, 3.4 kg K, and 4.8 kg Ca. Depending on the biomass of the stand, rubber trees had 380 to 700, 36 to 64, 530 to 980, and 750 to 1,360 kg of bound N, P, K, and Ca per hectare, respectively (Hytönen *et al*., 2019).

All smallholding farms use the same fertiliser formula (15-15-15) for rubber since it is widely found in the local area (Somboonsuke & Cherdchom, 2000). Common nutrition practices focus on applying macronutrients through synthetic fertilisers without considering micronutrients. However, micronutrients play a role in plant growth and development and contribute to plant tolerance against stressors and innate immunity, as they are involved in metabolic processes that control plant response and perception of stressors (Chrysargyris *et al*., 2022). The above results suggest that the occurrence of TPD in *Hevea* trees is caused by an imbalance in the amount of nutrients in the soil, especially Ca and Mg.

Chemical Components of Complete Organic Fertiliser

During the composting process, the organic fertiliser was closely monitored. The optimal fermentation period was determined by considering temperature and pH levels. The data analysis consistently demonstrated stable temperature and pH levels between day 15 and day 30 [Figure 2 (A)]. This indicates successful microbial activity that halted the decomposition process within the organic fertiliser pile [Figure 2 (B) and (C)]. Typically, organic fertiliser is

Table 3: Soil chemical properties were collected and analysed from the soils under trees affected by TPD and healthy trees (Pair sample t-test, N = 5; d.f. = 4)

Parameter	Mean ± SD		t-test	p-value
	Healthy	**TPD**		
pH (H_2O; 1:2)	5.13 ± 0.05	5.06 ± 0.06	1.594	0.172
EC (dS/m)	0.15 ± 0.02	0.15 ± 0.03	-0.113	0.915
OM (%)	1.93 ± 0.23	2.08 ± 0.37	-0.835	0.442
Fe (mg/kg)	55.43 ± 18.92	63.99 ± 16.43	-1.547	0.197
Zn (mg/kg)	0.58 ± 0.27	1.65 ± 1.39	-0.943	0.399
Avail. P (mg/kg)	7.52 ± 2.45	5.34 ± 1.33	0.876	0.421
Exch. K (mg/kg)	25.62 ± 6.68	26.35 ± 9.48	-0.149	0.888
Exch. Ca (mg/kg)	60.07 ± 17.22	34.11 ± 8.65	2.935	0.032*
Exch. Mg (mg/kg)	10.05 ± 1.87	7.30 ± 1.96	2.752	0.040*
Total N (%)	0.072 ± 0.09	0.06 ± 0.09	1.536	0.185

N = Number of samples, Healthy trees (n1) = 4, TPD affected trees (n2) = 4, SD = standard deviation, *$p < 0.05$.

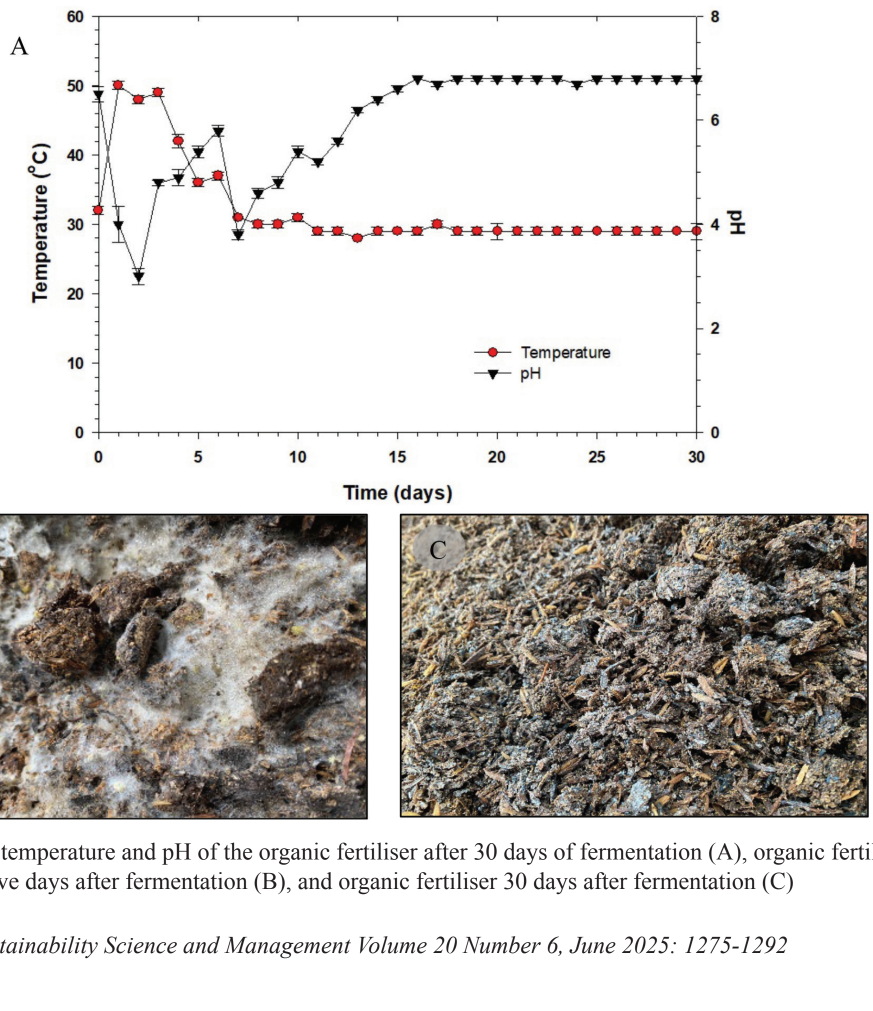


Figure 2: The temperature and pH of the organic fertiliser after 30 days of fermentation (A), organic fertiliser five days after fermentation (B), and organic fertiliser 30 days after fermentation (C)

produced by composting animal manure, human excrement, or plant materials such as straw and garden waste, with the aid of microorganisms fermenting at elevated temperatures (Chew *et al*., 2019).

The pH and EC values of complete organic fertiliser products in the study are represented in Table 4. The pH and EC were 7.75 and 8.81 dS/m, respectively. The pH values in the soil were revealed to be suitable for amendments and plant growth (Citak & Sonmez, 2011). However, the EC exceeded the standard metric of 4.0 dS/m. While the EC range of 2.0 to 4.0 dS/m for growing media (Briton, 2000), the elevated EC level could pose challenges for salt-sensitive crops. Thus, adjusting application rates or strategies to mitigate potential risks associated with salinity may be necessary. Moreover, the organic fertiliser demonstrated an abundance of nutrients, with higher organic matter and nutrient concentrations compared to standard benchmarks and similar products.

This nutrient richness underscores its potential as an effective soil amendment and plant growth enhancer. The measured organic matter content, high EC, and reported nutrient composition provide clear evidence that the organic fertiliser is rich in organic and inorganic nutrients. Correspondingly, these findings align with international standards and demonstrate its capacity to significantly enhance soil fertility and plant growth. This can be explained by optimising the level of organic mineralisation and releasing high levels of available nutrients (Hemidat *et al*., 2018).

Total organic carbon concentration, macronutrients, and micronutrients were abundant. The total organic matter content of the organic fertiliser was 60.19%. This was higher than the German standard (BioAbFV), which should range between 15.0% to 45.0%. It is also higher than the total organic matter content in a previous study, which ranged from 19.0% to 42.0% (Nghia & Tran, 2023). This indicates that organic fertiliser contains abundant macronutrients and micronutrients, reflecting a deliberate effort to enhance the quality and efficiency of the fertiliser. Building on this, organic fertiliser contains higher levels of organic matter and nutrient concentrations compared to standard benchmarks and related products. This nutrient abundance highlights its potential as a superior soil amendment and plant growth enhancer. The measured organic matter content, high EC, and reported nutrient composition provide straightforward evidence of the fertiliser's richness in both organic and inorganic nutrients. These findings align with international standards and confirm its capacity to significantly enhance soil fertility and promote plant growth.

The C/N ratio plays a vital role in the nutrient balance of a composting mixture, indicating the amount of carbon available in relation to N for the composting microorganisms. The ratio of C/N was 20.54, which indicates high levels of nutrients beneficial for soils and plants, enabling rapid mineralisation of nutrients from organic matter for plant uptake. These results agree with those of Dougherty (1999), who asserted that the C/N ratio ranged from 15:1 to 20:1, which is ideal for ready-to-use compost. Moreover, the N content is 1.70%, indicating that the product is an excellent organic fertiliser, which is in agreement with other research findings conducted by Chaudhary *et al*. (2017).

The total P and K content of the organic fertiliser products were 4.60% and 3.13%, respectively. These products had higher total P and K content, suggesting that composting and digesting organic waste by microorganisms enhanced the nutrient qualities of the organic fertiliser. In contrast, the concentration of CaO, MgO, and Na_2O in organic fertilisers ranged from 4.27%, 0.7%, and 1.48%, respectively. This suggests that composting and the use of microorganisms to decompose source materials are highly beneficial methods for producing quality organic fertiliser. It contains high NPK nutrient concentrations and thus could supply necessary nutrients for plant uptake. These results are similar to those of Hemidat *et al*. (2018), who demonstrated that nutrient concentration in organic fertilisers was boosted through composting and fermentation processes due to the roles the microbial consortia play in the solubilisation of carbohydrates, protein, and lipids.

Final product quality findings indicated that concentrations of five heavy metals (Pb, Cd, As, Cu, and Cr) were significantly within the set limits and were much lower compared to European standards (Table 5).

Organic Fertiliser Effect on Soil Nutrient and Latex Yields

The application of organic fertilisers every six months yielded significant improvements in latex productivity (% DRC and rubber dry weight) from *Hevea* trees over a one-year period. The use of organic fertiliser led to significantly higher % DRC and rubber dry weight compared to the application of chemical fertilisers ($p < 0.05$), as displayed in Figure 3 (A) and (B). However, only the latex dry weight of the rubber tree before organic fertiliser application in June and October was higher than the rubber tree that had received organic fertiliser.

Significant progress has been observed in rubber plantations using organic fertilisers, particularly in terms of increased Mg content ($p < 0.01$). Table 6 reveals substantial improvements in Mg levels, which rose by a factor of 3.81

Table 4: Chemical properties of produced organic fertiliser

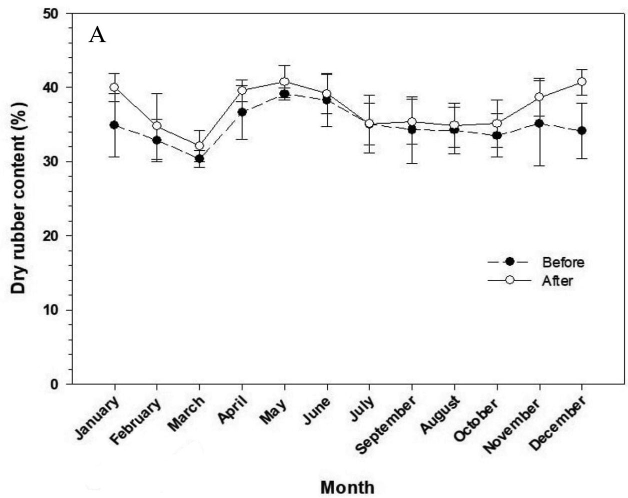
Properties	Value
pH	7.75
EC (dS/m)	8.81
Total organic matter (%)	60.19
Total organic carbon (%)	34.91
N (%)	1.70
C/N	20.54
Total phosphorus (%)	4.60
Total potassium (%)	3.13
CaO (%)	4.27
MgO (%)	0.70
Na_2O (%)	1.48
S (%)	0.67
Fe (%)	0.01

Table 5: Heavy metal concentrations in compost compared with the German standard

Parameter	Value (mg/kg)	Average Limit Values of EU Countries	
		Class I	Class II
As	2.12	-	-
Cd	0.09	0.7	1.5
Pb	2.36	100	150
Cu	82.35	100	150
Cr	2.47	100	150

Source: Hogg *et al*. (2002)

times. These findings align with the studies of Vrignon-Brenas *et al*. (2019), which demonstrated that N, P, K, and Mg fertilisation improved rubber tree growth and shortened the pre-harvest period. They also quantified nutrient (N, P, K, Ca, and Mg) losses due to leaching in rubber tree plantations. In addition, these findings signified that the developed bio-organic fertiliser holds great potential for enhancing rubber cultivation practices. Notably, good organic fertiliser are materials with a well-defined chemical composition and high nutritional value. They play a crucial role in supplying essential nutrients for the growth of plants (Möller & Schultheiß, 2015; Rajan & Anandhan, 2015). By enhancing soil structure, providing a diverse range of plant nutrients, and introducing beneficial microorganisms, organic fertilisers have become widely used in agricultural systems due to their positive effects on soil quality and crop yields (Singh *et al*., 2015; Maltas *et al*., 2018). Additionally, the utilisation of organic fertiliser brings about significant changes in Cation Exchange Capacity (CEC) and soil moisture content, impacting the structure and composition of soil fauna communities, particularly in acidic soils (Zelles *et al*., 1992; Abbott & Murphy, 2007).



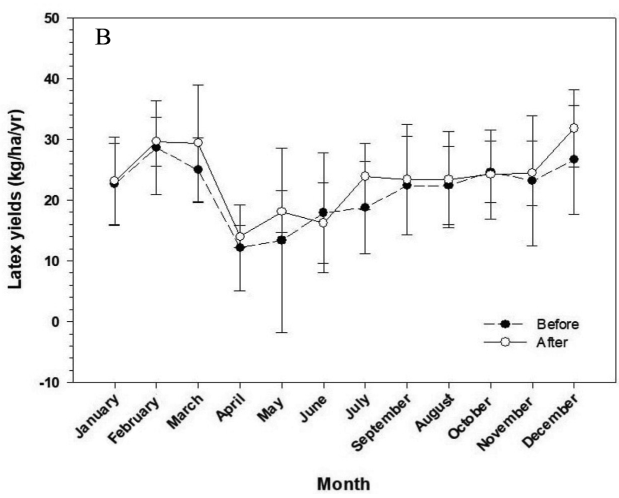


Figure 3: Effect of organic fertiliser showing the mean SD for latex yields (A) % DRC and (B) latex dry weight of *Hevea* trees. Bars indicate the Standard Deviation (SD)

Table 6: Soil nutrients before and after applying organic fertiliser to the soil

Parameter	Mean ± SD		t-test	p-value
	Before	After		
pH (H_2O; 1:2)	4.44 ± 0.134	4.75 ± 0.230	-0.179	0.365
EC (dS/m)	0.345 ± 0.039	0.44 ± 0.025	-1.956	0.478
OM (%)	2.045 ± 0.361	2.00 ± 0.397	0.098	0.808
Avail. P (mg/kg)	19.20 ± 13.26	41.87 ± 26.36	-0.768	0.291
Exch. K (mg/kg)	49.55 ± 15.71	53.89 ± 21.643	-0.162	0.082
Exch. Ca (mg/kg)	97.32 ± 8.64	488.62 ± 184.250	-2.121	0.090
Exch. Mg (mg/kg)	17.763 ± 4.81	67.67 ± 27.51	-1.787	0.006**
Total N (%)	0.103 ± 0.023	0.123 ± 0.022	-0.0639	0.705

N = Number of samples: Before applying organic fertiliser (n1) = 4; after applying organic fertiliser (n2) = 4, independent sample t-test, N = 6, SD = standard deviation, ** $p < 0.01$.

Organic Fertiliser and Micronutrients on TPD Hevea Trees

During this experiment, our main goal was to devise a cost-effective approach for administering organic fertiliser and micronutrients to small-scale rubber farms. We decided to replace the micronutrient solution with granular chemical fertilisers, which were combined with organic fertiliser and MG before being applied to the soil beneath TPD *Hevea* trees (Figure 4). The findings demonstrated the application of MS to the bark, along with MS and organic fertiliser, to the soil (referred to as treatment T1). This led to a significant reduction in DCL, from 77.6% to 13% [Figure 5 (A)], with a p-value of less than 0.05. Additionally, treatment T3, which incorporates the application of organic fertiliser in conjunction with MG-500 g, demonstrated superior latex yields compared to the alternative treatments [Figure 5 (B) and (C)]. However, there was no statistically significant difference in each DRC value before the trial and after the experiment. Notably, T4 yielded the highest percentage of DRC [Figure 5 (D)].

Figure 4: Latex flow immediately after tapping, 1 month after the first treatment with OF and MS on scraped bark and soil in partially TPD *Hevea* trees. T1: TPD-affected trees with MS applied to the bark and 10 kg of organic fertiliser and 2,000 ml of MS applied to the soil (Control); T2: TPD-affected trees with 10 kg of organic fertiliser and 100 g of MG; T3: TPD-affected trees with 10 kg of organic fertiliser and 500 g of MG; T4: TPD-affected trees with 10 kg of organic fertiliser and 1,000 g of MG

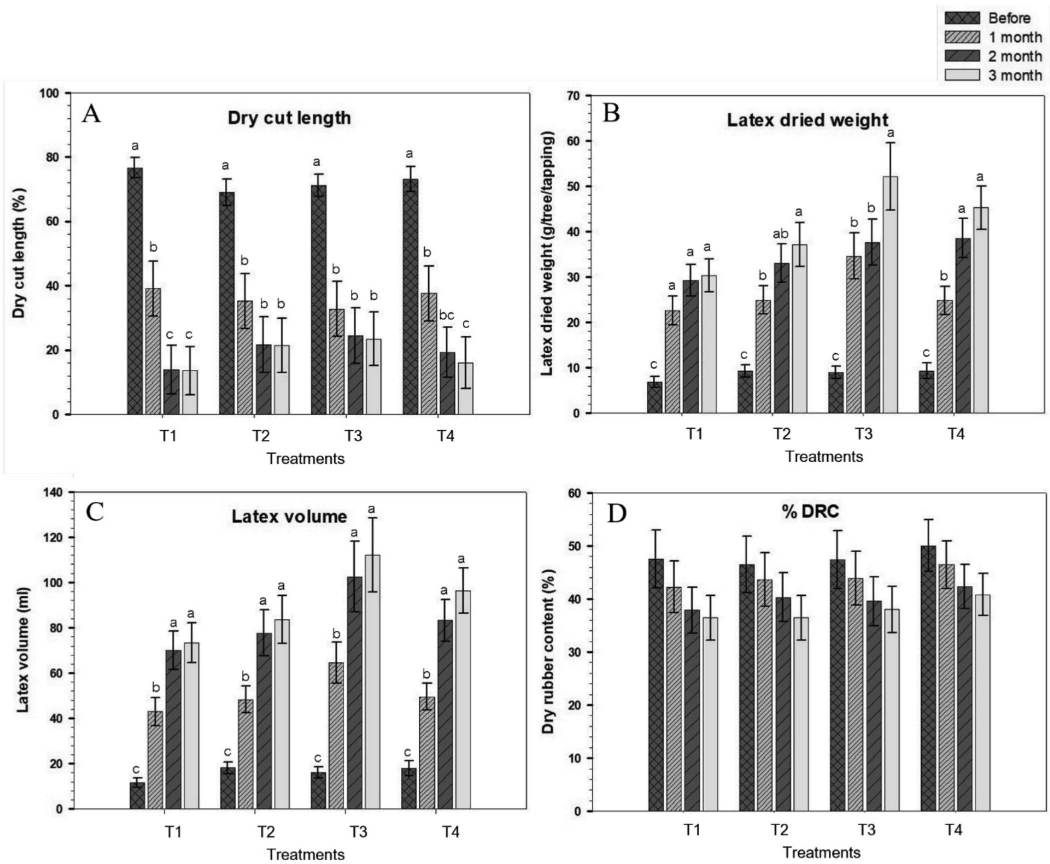


Figure 5: Effect of TPD *Hevea* trees with organic fertiliser, MS, and MG on dry cut length (A), latex yields on the latex dried weight (B), latex yields based on the latex volume (C), and dry cut length (D). Different letters within treatment indicate significant differences at the $p < 0.05$ level, according to Duncan's multiple range test method. T1: TPD-affected trees with MS applied to the bark and 10 kg of organic fertiliser and 2,000 ml of MS applied to the soil (control); T2: TPD-affected trees with 10 kg of organic fertiliser and 100 g of MG; T3: TPD-affected trees with 10 kg of organic fertiliser and 500 g of MG; T4: TPD-affected trees with 10 kg of organic fertiliser and 1,000 g of MG

The initial symptom is linked to an overproduction of ROS. This oxidative stress in latex cells leads to the peroxidation of the membrane of vacuo-lysosomal particles called lutoids, which subsequently release Hevein, an agglutinin protein (Chrestin *et al*., 1984). The process causes the agglutination of rubber particles, obstructing latex flow after tapping (Zhang *et al*., 2017). Trees affected by ROS-TPD can resume normal latex flow after a resting period. The second symptom involves an irreversible cessation of latex flow and the development of Brown Bast (BB). Meanwhile, BB-TPD is characterised by bark deformation due to thylosoid formation, lignified gum, and abnormal parenchyma cell division (Herlinawati *et al*., 2022). A study by Lertpanyasampatha *et al*. (2014) reported other physiological diseases, referred to as bark or trunk phloem necrosis. According to de Faÿ and collaborators, these physiological diseases are identical to or variants of TPD (de Faÿ, 2011). Trees affected by TPD can occasionally be treated by bark scraping and the application of chemicals to encourage bark renewal. However, this process is expensive and not commonly used.

Bark treatment with a micronutrient solution such as MS, organic fertiliser, and MS applied to the soil, consistently reduces DCL and increases latex yield in TPD-affected trees. The increase in latex yield is more significant in trees with partial TPD compared to those with total TPD, indicating that bark treatment is more effective during the early stages of the syndrome. However, treatments on trees with total TPD result in poor disease recovery compared to those with partial TPD. This suggests that the treatment is less effective when applied during advanced stages of TPD, where histological deformation of the bark occurs due to thylosoid formation and lignified gum. Furthermore, the abnormal parenchyma cell division eventually leads to irreversible total latex dryness and is associated with cyanogenesis.

A study by Suwandi *et al*. (2018) demonstrated the effectiveness of using SWCE as a bark treatment to reduce the incidence of TPD in *Hevea* trees and increase latex yield. In particular, the main plant nutrients applied in the form of MS were nitrate, Ca, and amino acids, with a specific emphasis on Ca. Calcium ion (Ca^{2+}) is an essential element for plant growth and development, both under normal and stressful conditions. It plays a crucial role in programmed cell death pathways that protect plants from hypersensitive responses. Emerging evidence suggests that changes in cellular Ca handling and increased cytosolic Ca levels may be associated with apoptotic signalling. Note that the excessive accumulation of ROS can lead to oxidative stress, resulting in cell death and potential plant demise.

The primary sites of ROS production in plant cells are mitochondria, chloroplasts, and peroxisomes. As such, plants possess mechanisms to regulate ROS balance in response to abiotic stress, including enzymatic and non-enzymatic clearance mechanisms. In addition, the CCCH Zn finger protein is involved in this regulatory process. Ca pulses, induced by abiotic stress, serve as secondary messengers that initiate the regulation mediated by the CCCH Zn finger protein, which shuttles between the cytoplasm and nucleus. This regulation occurs through Ca^{2+}-mediated abscisic acid (ABA) or Mitogen-activated protein kinases (MAPKs) transcriptional regulation. Ca^{2+} functions as a second messenger in plant cells and is crucial in various signalling transduction pathways. Consequently, alterations in Ca sensors or Ca-binding proteins can impact these pathways (Buakong *et al*., 2023).

In higher plants, four major classes of Ca-binding proteins have been identified and studied, namely Ca-Dependent Protein Kinases (CDPKs or CPKs), Calmodulins (CaMs), CaM-like proteins (CMLs), and Calcineurin B-like proteins (CBLs). Mg is an essential nutrient for numerous fundamental physiological and biochemical processes in plants, including chlorophyll synthesis, production and transportation of photoassimilates, enzyme activation, and protein synthesis (Ranty *et al*., 2006). This research highlights that soil nutrients are crucial N, P, K, Ca, Mg, and other micronutrients, including the amount of each nutrient. Additionally, the development of organic fertilisers provides an alternative for farmers to reduce production costs. Therefore, it is crucial for farmers to rely on themselves rather than external production factors.

Conclusions

In conclusion, this study provides valuable insights into the impact of soil nutrients on *Hevea* trees affected by TPD. To address these challenges, we developed a formula for organic fertiliser and conducted a comprehensive plant nutrient analysis, confirming the high quality of the fertiliser. Accordingly, the appropriate micronutrients were analysed and combined with the organic fertiliser. The resulting mixture was applied to the soil beneath *Hevea* trees affected by TPD. Our study focused on both partially and fully affected TPD rubber trees. The results demonstrated that the treatment of TPD-affected *Hevea* trees (applying the MS nutrient solution to the bark and using the organic fertiliser and MS in the soil) significantly reduced the length of cut dryness from 77.6% to 13% ($p < 0.05$).

Furthermore, applying the organic fertiliser with 500 g of MG resulted in the highest latex yield compared to the other treatments. These findings suggest that applying the MS nutrient solution to the bark and using the organic fertiliser in the soil could effectively treat *Hevea* trees partially affected by TPD.

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Conflict of Interest Statement

The authors declare no conflict of interest among authors or any other individual or organisation.

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