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Effects of mounding on soil properties, root development, and physiological responses of *Ganoderma boninense*-infected and uninfected oil palms

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ABSTRACT

Basal stem rot (BSR), caused by *Ganoderma boninense*, is a major disease in oil palm plantations, leading to significant losses. Currently, there is no fully effective method to control this disease. This study evaluated the effects of mounding techniques on root development in both *Ganoderma*-infected and uninfected oil palms over 8 months. The research was conducted across six plantations in North Sumatra, where root biomass was measured by uncovering a quarter of the mounded area and analyzing the soil's physical and chemical properties. The results showed that, although most soil properties were comparable, cation exchange capacity (CEC) and magnesium (Mg) levels were higher in uninfected palms. Root growth increased in both infected and uninfected palms from three to eight months after mounding, but by the seventh and eighth months, the root biomass in infected palms was lower compared to uninfected palms. Infected palms primarily showed the growth of primary-like roots, whereas uninfected palms exhibited more extensive tertiary and quaternary roots. The study concluded that while mounding stimulates root development, *Ganoderma* infection limits this growth. These findings have important implications for improving disease management strategies in oil palm plantations.

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1. INTRODUCTION

The oil palm (*Elaeis guineensis*) is a strategic plantation crop that makes substantial contributions to both the global and national economies, particularly in tropical countries such as Indonesia. During the 2022–2023 marketing year, Indonesia produced 46.5 million metric tons of crude palm oil (CPO), the highest output worldwide, accounting for approximately 59% of global palm oil production (Ostfeld & Reiner, 2024). The palm oil industry generates around USD 28.45 billion in export value and contributes approximately 3.5% to Indonesia's GDP (Judijanto, 2025). As the primary source of vegetable oil, palm oil is used in about half of all packaged consumer goods. It supports a wide range of industrial sectors, including food, cosmetics, pharmaceuticals, and biofuels (Ostfeld & Reiner, 2024). However, oil palm production faces numerous challenges that can reduce productivity and quality. One of the main issues is the threat of disease, which can jeopardize the sustainability of oil palm plantations (Syarovy et al., 2023).

One of the most detrimental diseases in oil palm production is basal stem rot (BSR), caused by the fungus *Ganoderma boninense.* This disease can lead to substantial production losses, with yield reductions of up to 80% reported in severely affected plantations, especially after multiple planting cycles (Paterson, 2007). Oil palms infected with *Ganoderma* exhibit symptoms such as the emergence of spear leaves, frond fracture, and eventual stem breakage (Husin et al., 2021; Liaghat et al., 2014). In oil palm plantations in North Sumatra, the incidence of BSR has been found across various generations of oil palms, with an infection rate of 24.02% in the first generation, 41.42% in the second generation, and 58.85% in the third generation (Wijayanti et al., 2024). These generations refer to successive replanting cycles on the same land, each spanning approximately 25–30 years. The impact of this disease not only reduces yield but also threatens the sustainability of oil palm plantations (Paterson, 2019).

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Ganoderma, a genus of pathogenic fungi, poses a serious threat to several crops, particularly oil palm. The species *Ganoderma boninense* is considered the most virulent, as it infects the basal stem of the palm, leading to progressive tissue decay, vascular dysfunction, and ultimately plant death. In oil palm plantations, BSR typically emerges around 10–12 years after planting, with infection rates rising from 1–2% to over 25% by the replanting age of approximately 25 years. The pathogen spreads primarily through soil-borne spores and root contact between diseased and healthy palms (Paterson, 2007).

Various studies have been conducted to understand the mechanisms of *Ganoderma* infection and explore ways to control its spread. Some studies have shown that cultural techniques, such as inoculum sanitation, hole-in-hole planting systems, surgery and mounding, and isolation trenches, can help reduce the impact of *Ganoderma* attacks (Priwiratama et al., 2020; Susanto et al., 2013). The results indicate that these four cultural control methods effectively prevent *Ganoderma* infection at the early stages of oil palm development. Inoculum sanitation can prevent *Ganoderma* infection for up to two years after treatment (YAT). The hole-in-hole system effectively suppresses BSR development for up to seven YAT. Surgery and mounding can extend the lifespan of infected palms by up to three YAT, while isolation trenches can prevent the spread of the disease for up to two YAT fields (Priwiratama et al., 2014).

Mounding is one of the cultural techniques considered to enhance the resistance of oil palms to *Ganoderma* infection. This technique involves piling soil around the palm's trunk base, strengthening the root system and improving plant health. Several studies have shown that mounding can help improve the physiological condition of the palm, promote better root development, and increase bacterial colony-forming units (CFU), even in palms already infected with *Ganoderma* (Kheng et al., 2013; Priwiratama et al., 2014; Suwardi, 2021).

This study aimed to evaluate the effects of mounding on root development, soil chemical properties, and physiological traits of oil palms, with a specific focus on differences between *Ganoderma*-infected and uninfected palms. While previous studies have generally explored mounding as a field management technique, this research provides a more detailed and integrated assessment of root biomass dynamics, nutrient availability, particularly cation exchange capacity (CEC) and magnesium content, vegetative growth indicators, leaf greenness, and root morphological responses over time. The findings offer new insights into how mounding influences palm performance under *Ganoderma* pressure and support more targeted disease management strategies.

2. MATERIAL AND METHODS

This study was conducted in February 2024 across six oil palm plantations located in North Sumatra Province. The plantations are situated in the districts of Bosar Maligas, Tanah Jawa, and Dolok Panribuan (Simalungun Regency), Perbaungan (Serdang Bedagai Regency), and Aek Kuasan and Air Batu (Asahan Regency) (Fig. 1). It focused on oil palms aged between 14 and 19 years, which are highly susceptible to *Ganoderma* infection. Figure 2 presents all stages of the study.

The study began with an inspection of all mounded areas, mainly focusing on the age of the mounds. Following the inspection, it was determined that the mounds selected for this study were 3, 5, 6, 7, and 8 months old. The specifications of the mounds were measured by determining each mound's radius (r) and height (h). The measurements of r and h were taken from four sides of each palm. Figure 3 illustrates these measurements.

The determination of *Ganoderma*-infected palms was based on physical criteria, such as more than three spear leaves, fewer than 17 fresh fronds, surrounding palms exhibiting similar symptoms, and *Ganoderma* fruiting bodies. Subsequently, infected and uninfected palms were validated using vegetative, generative, and chlorophyll content parameters. Vegetative and generative parameters were measured, including rachis length, petiole width and thickness, Petiole Cross Section (PCS), the number of leaflets, leaf area, and leaf area index. Chlorophyll content was measured by lowering fronds 1, 9, 17, and 25. The leaflets typically used as the leaf sampling unit (LSU) were selected to assess chlorophyll content. The instrument used for measuring chlorophyll content was the SPAD-502 from Konica Minolta, Tokyo, Japan.

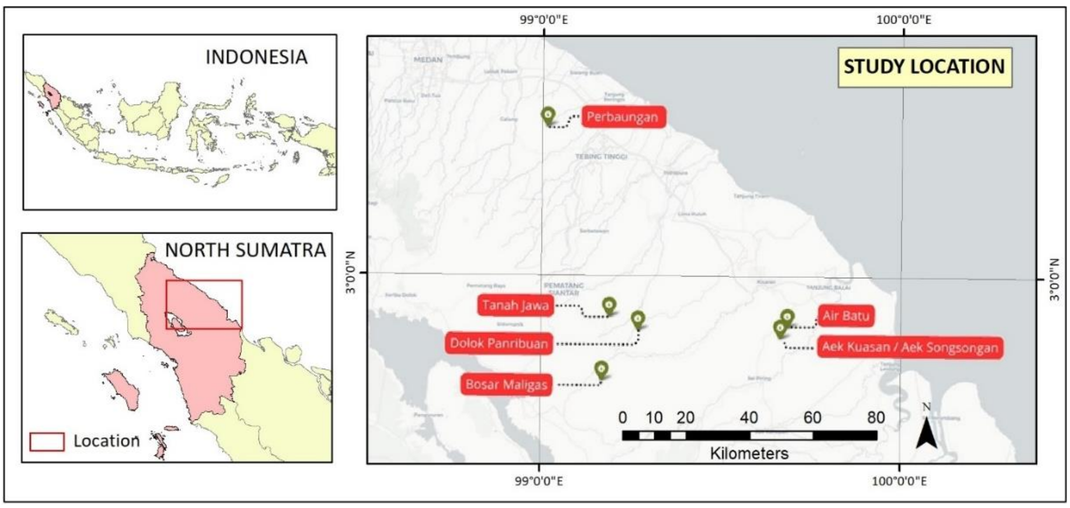


Figure 1. Locations of six oil palm plantations surveyed across North Sumatra Province, Indonesia.

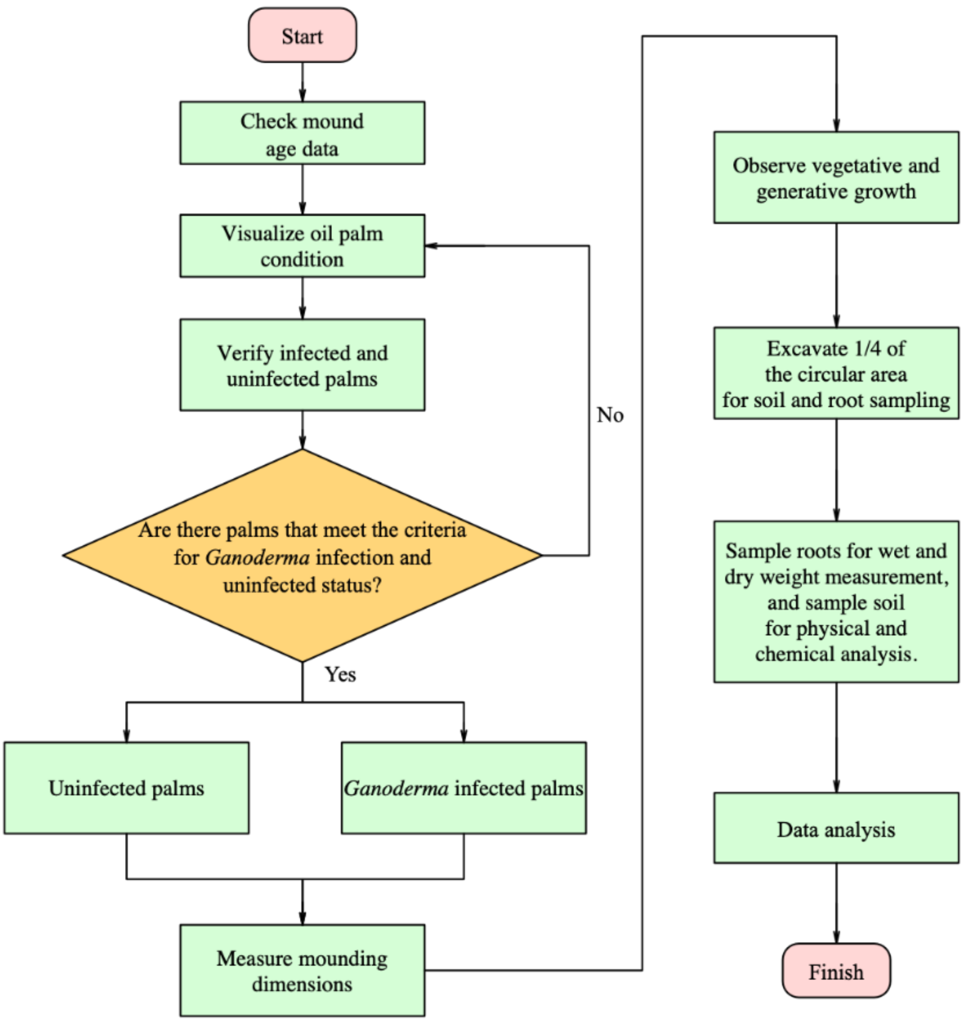


Figure 2. All stages of the research.

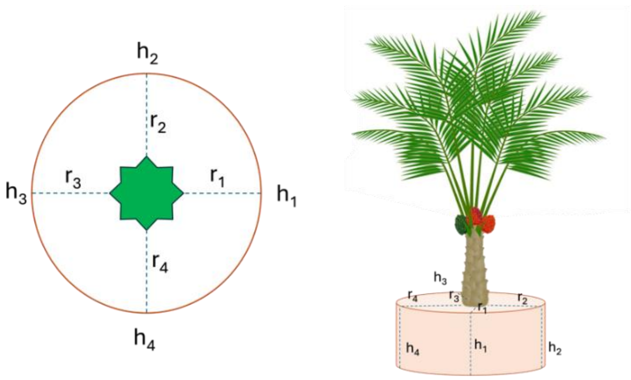


Figure 3. Illustration of mounding radius (r) and height (h) measurements.

Root samples were collected by excavating a quarter (1/4) section of the mounded area, starting at the soil surface and extending down to the original soil level prior to mounding (Fig. 4). Roots within the excised section were collected and weighed to determine their fresh weight. Root dry weight was determined by oven-drying them at 60–80°C for approximately 72 hours until they reached a constant weight.

The analysis was conducted using descriptive statistics, including the calculation of mean, median, maximum, minimum, and standard error values. Additionally, a t-test was performed to assess the significance of differences between infected and uninfected plants. All analyses were performed using the Python programming language (version 3.10) in the Google Collaboratory environment, utilizing the pandas (v1.5.3), numpy (v1.24.2), matplotlib (v3.7.1, and scipy (v1.10.1) libraries.

3. RESULTS

3.1. Mounding specification

The standard mounding specifications (radius of 150 cm and height of 50 cm) were applied across various plantations based on standard operational procedures implemented in the field. Mounding was specifically conducted on oil palm stands aged 14 years and above, particularly in areas with a high incidence or increasing trend of *Ganoderma* infection. This study measured mounding in a total of 28 palms, consisting of 14 *Ganoderma*-infected palms (infected group) and 14 uninfected palms (uninfected group). In the uninfected group, the average mounding radius (r) was 155.2 cm, ranging from 120 cm to 250 cm, with a median of 150 cm. Conversely, the infected group's average mounding radius was 154.3 cm, ranging from 130 cm to 180 cm, with a median of 150 cm. These data indicate that mounding was performed consistently in accordance with the 150 cm radius standard in both groups, despite broader variation observed in the uninfected group; however, this variation did not show a significant difference.

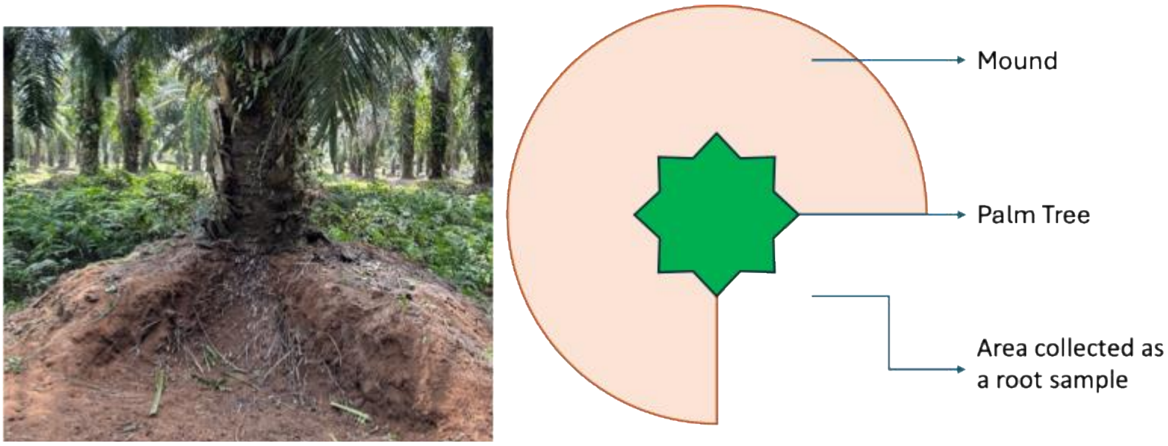


Figure 4. Illustration of mound excavation for root samples.

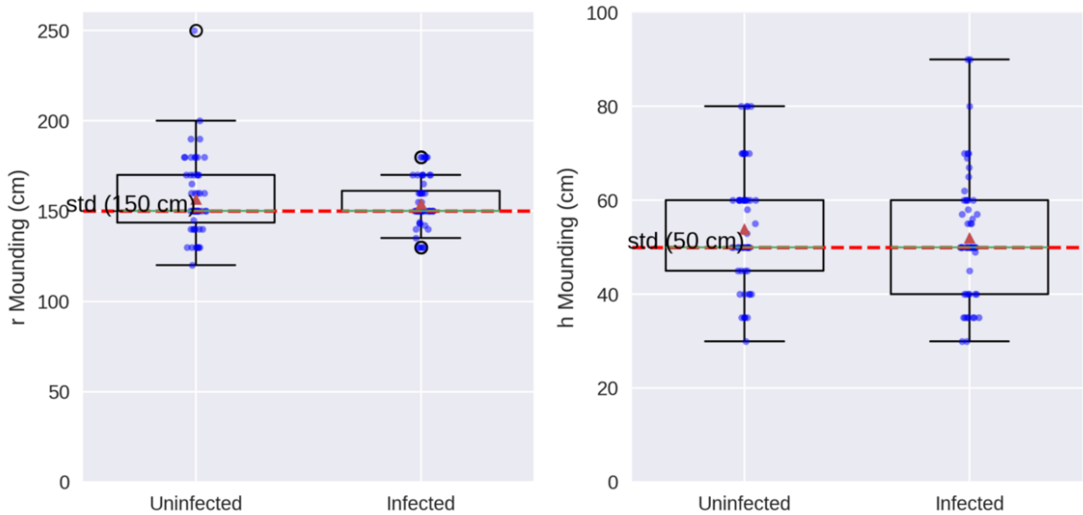


Figure 5. Boxplot of radius (r) and height (h) measurements in *Ganoderma*-infected and uninfected palms.

Table 1. Mean, median, minimum, maximum, standard error, and t-test results for radius (r) and height (h) in *Ganoderma*-infected and uninfected.

Variables	Statistic	Uninfected	Infected	t Test
r Mounding (cm)	Mean	156.96	154.32	ns
	Median	150.00	150.00	
	Minimum	120.00	130.00	
	Maximum	250.00	180.00	
	Standard Error	2.95	1.86	
h Mounding (cm)	Mean	53.95	52.05	ns
	Median	50.00	50.00	
	Minimum	30.00	30.00	
	Maximum	80.00	90.00	
	Standard Error	1.68	1.79	

Notes: * = significant ($p < 0.05$), indicating that the difference between the Non-Infected and Infected groups is statistically significant; ns = not significant ($p \geq 0.05$), indicating that the difference between the Non-Infected and Infected groups is not statistically significant.

For the mounding height parameter, the uninfected group showed an average height of 52.7 cm, ranging from 30 to 80 cm, and a median of 50 cm. In the infected group, the average mounding height was 52.1 cm, ranging from 30 cm to 90 cm with a median of 50 cm. These results indicate that the mounding height standard of 50 cm was consistently maintained in both groups, with a broader variation in height observed in the infected group, though no significant difference was detected. Overall, the boxplot and the table of mounding specification measurements are presented in Figure 5 and Table 1.

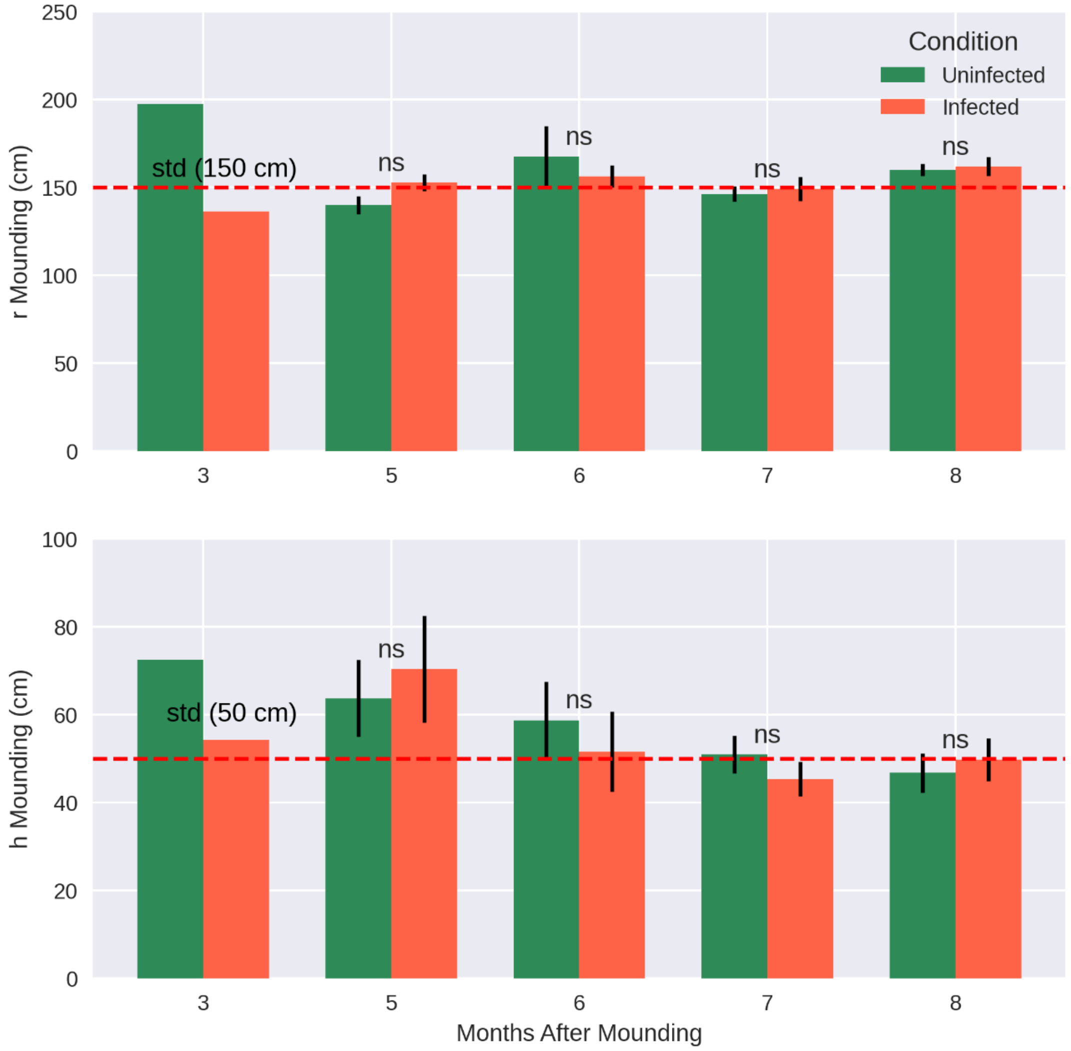


Figure 6. Radius (r) and height (h) measurements in *Ganoderma*-infected and uninfected plants at 3, 5, 6, 7, and 8 months after mounding.

Figure 6 presents the mounding specifications at various ages following the mounding process. Overall, no significant differences were observed in the mounding dimensions, specifically regarding radius and height, between *Ganoderma*-infected and uninfected palms. However, the mounding height tended to decrease as the mound aged. This reduction was likely due to surface runoff, which caused the mound height to diminish over time.

3.2. Plant growth

The selection of plants based on precise criteria is crucial for distinguishing between *Ganoderma*-infected and uninfected palms. Figure 7 illustrates the physical characteristics of both *Ganoderma*-infected and uninfected palms. Generally, uninfected palms exhibit healthy growth, ample fruit reserves, and overlapping leaf areas between palms. In contrast, *Ganoderma*-infected palms show stunted physical growth, lack fruit reserves, have many unopened leaves, and reduced leaf areas, as indicated by canopies that do not overlap.

Figure 8 and Table 2 present boxplots of the measurements for rachis length, petiole cross-section, leaf area, leaf area index, number of fronds, and number of bunches. For rachis length, uninfected palms range between 553.00 cm and 705.00 cm, with an average of 633.75 ± 1.05 cm. In contrast, *Ganoderma*-infected palms exhibit a significantly shorter rachis length, averaging only 154.25 ± 0.67 cm (Table 2). The petiole cross-section shows a similar pattern. Uninfected palms have a cross-sectional area ranging from 46.00 cm^2 to 82.50 cm^2, with an average of 61.27 ± 1.05 cm^2, whereas infected palms have a significantly reduced petiole cross-section, averaging only 12.69 ± 0.67 cm^2 (Table 2). The leaf area in uninfected palms varies between 9.57 m^2 and 16.07 m^2, with an average of 12.98 ± 1.05 m^2, while in infected palms, the leaf area is significantly reduced, averaging only 2.90 ± 0.67 m^2 (Table 2).

The Leaf Area Index (LAI) also reflects this trend, with *Ganoderma*-infected plants having an LAI of only around 0.79, compared to uninfected palms with an LAI ranging from 5.35 to 7.12. The number of fronds and bunches in uninfected palms is also significantly higher than in infected palms. Uninfected palms have between 30 and 41 fronds, with an average of 34.00, whereas infected palms have an average of only 13.25 fronds. Similarly, the number of bunches in uninfected palms averages 4.63, while infected palms average only 1.25 bunches.

Figure 7. The physical condition of uninfected palms (left) and *Ganoderma*-infected palms (right).

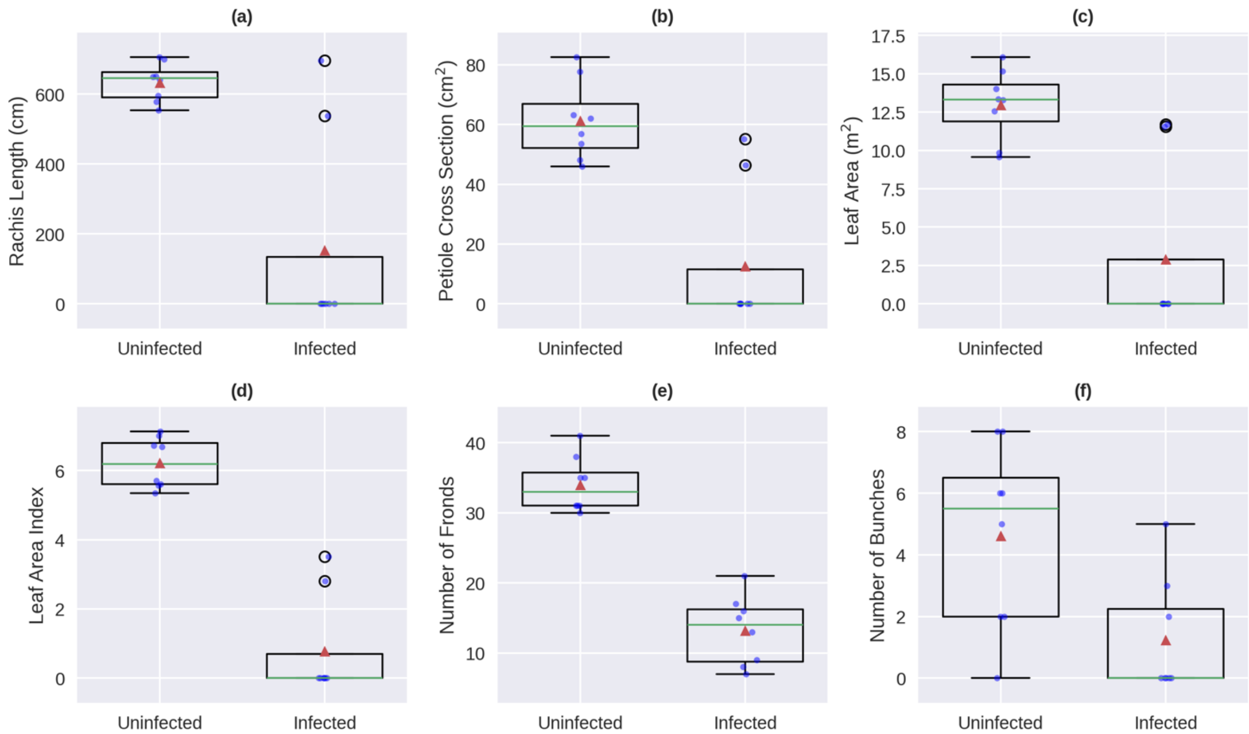


Figure 8. Mean, median, minimum, maximum, standard error, and t-test values for rachis length (a), petiole cross-section (b), leaf area (c), leaf area index (d), number of fronds (e), and number of bunches (f) in *Ganoderma*-infected and uninfected palms.

All variables demonstrated significant differences between uninfected and *Ganoderma*-infected palms, indicating that the measurements of vegetative variables validated the visual observations. Additionally, some variables, such as rachis length, petiole cross-section, leaf area, and leaf area index, showed a minimum value of zero. This was due to the absence of the 17^{th} frond, which was used as a reference for these measurements.

Table 2. Mean, median, minimum, maximum, standard error, and t-test values for rachis length, petiole cross-section, leaf area, leaf area index, number of fronds, and number of bunches in *Ganoderma*-infected and uninfected palms.

Variables	Statistic	Uninfected	Infected	t Test
Rachis Length (cm)	Mean	633.75	154.25	*
	Median	645.00	0.00	
	Minimum	553.00	0.00	
	Maximum	705.00	696.00	
	Standard Error	1.05	0.67	
Petiole Cross Section (cm^2)	Mean	61.27	12.69	*
	Median	59.45	0.00	
	Minimum	46.00	0.00	
	Maximum	82.50	55.10	
	Standard Error	1.05	0.67	
Leaf Area (m^2)	Mean	12.98	2.90	*
	Median	13.32	0.00	
	Minimum	9.57	0.00	
	Maximum	16.07	11.68	
	Standard Error	1.05	0.67	
Leaf Area Index	Mean	6.22	0.79	*
	Median	6.19	0.00	
	Minimum	5.35	0.00	
	Maximum	7.12	3.51	
	Standard Error	1.05	0.67	
Number of Fronds	Mean	34.00	13.25	*
	Median	33.00	14.00	
	Minimum	30.00	7.00	
	Maximum	41.00	21.00	
	Standard Error	1.05	0.67	
Number of Bunches	Mean	4.63	1.25	*
	Median	5.50	0.00	
	Minimum	0.00	0.00	
	Maximum	8.00	5.00	
	Standard Error	1.05	0.67	

Notes: * = significant ($p < 0.05$), indicating that the difference between the Non-Infected and Infected groups is statistically significant; ns = not significant ($p \geq 0.05$), indicating that the difference between the Non-Infected and Infected groups is not statistically significant.

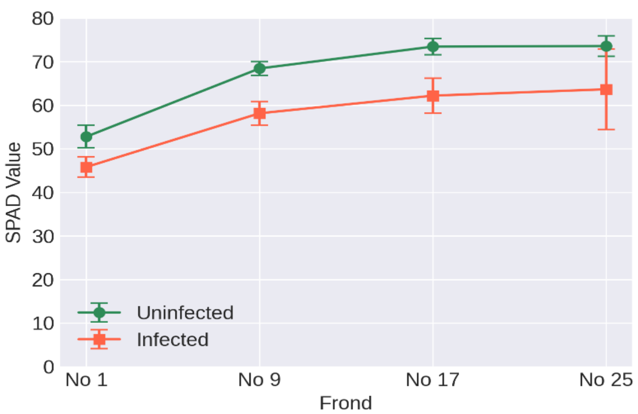


Figure 9. SPAD values in *Ganoderma*-infected and uninfected palms from Frond No. 1 to 25.

Based on the results of chlorophyll content measurements using the SPAD (Konica Minolta SPAD 502) on various fronds (Fig. 9 & Table 3), there were significant differences between uninfected and *Ganoderma*-infected palms. For Frond No. 1, the average SPAD value for uninfected palms was 52.78 ± 2.58, with a range from 35.25 to 65.47, while in infected palms, the average SPAD value was lower at 45.81 ± 2.58, with a range from 33.02 to 65.7. A similar pattern was observed in Frond No. 9, where uninfected palms had an average SPAD value of 68.43 ± 1.62, ranging from 57.9 to 78.28, whereas infected palms had an average value of 58.14 ± 2.72, with a range from 38.07 to 69.05.

Similarly, for Frond No. 17, the average SPAD value for uninfected palms was 73.45 ± 1.82, with a range from 56.98 to 81.92, whereas in infected palms, the average SPAD value decreased to 62.18 ± 4.03, with a range from 48.1 to 75.15. Frond No. 25 also showed a decline in SPAD values in infected palms, averaging 63.66 ± 9.22 compared to 73.58 ± 2.30 in uninfected palms. The range of values in uninfected palms was between 49.02 and 84.95, while in infected palms, it ranged from 45.53 to 75.7. These data indicate that *Ganoderma* infection consistently reduces SPAD values across various fronds, reflecting its negative impact on palm health.

Table 3. Mean, median, minimum, maximum, standard error, and t-test values for SPAD values measured on frond positions No. 1, 9, 17, and 25 in *Ganoderma*-infected and uninfected oil palms.

SPAD Variables	Statistic	Uninfected	Infected	t Test
Frond No 1	Mean	52.78	45.81	*
	Median	54.77	44.47	
	Minimum	35.25	33.02	
	Maximum	65.47	65.70	
	Standard Error	2.58	2.28	
Frond No 9	Mean	68.43	58.14	*
	Median	67.50	57.63	
	Minimum	57.90	38.07	
	Maximum	78.28	69.05	
	Standard Error	1.62	2.72	
Frond No 17	Mean	73.45	62.18	*
	Median	74.50	67.03	
	Minimum	56.98	48.10	
	Maximum	81.92	75.15	
	Standard Error	1.82	4.03	
Frond No 25	Mean	73.58	63.66	*
	Median	75.33	69.73	
	Minimum	49.02	45.53	
	Maximum	84.95	75.70	
	Standard Error	2.30	9.22	

Notes: * = significant ($p < 0.05$), indicating that the difference between the Non-Infected and Infected groups is statistically significant; ns = not significant ($p \geq 0.05$), indicating that the difference between the Non-Infected and Infected groups is not statistically significant.

Figure 10. Illustration of chlorophyll content measurements using the SPAD (Konica Minolta SPAD 502), showing low values (a) and high values (b).

Figure 10 provides a visual illustration of chlorophyll content measurement using the SPAD meter, showing the contrast between low values (a) typically associated with yellow leaves, and high values (b) observed in green, healthy leaves.

3.3. Soil Physical and Chemical Properties

Figure 11 and Table 4 present boxplots of the distribution of three soil physical variables, sand (%), silt (%), and clay (%), comparing the infected and uninfected conditions. For sand (%), the range of values in the infected condition was between 42% and 84%, while in the uninfected condition, it ranged from 50% to 82%. The median sand (%) in the infected condition was 80%, slightly higher than the 75% in the uninfected condition. The mean sand (%) in the infected condition was 70.9 ± 5.20%, also slightly higher than 69.8 ± 3.79% in the uninfected condition. The t-test results indicated no significant difference between the two groups.

For the silt (%) variable, the range of values in the infected condition was between 5% and 41%, while in the uninfected condition, it ranged from 7% to 39%. The median silt (%) in the infected condition was 9.0%, slightly lower than the 13% in the uninfected condition. The mean silt (%) also showed a similar trend, with the infected condition at 12.1 ± 3.76% and the uninfected condition at 15.8 ± 2.85%. The t-test results again showed no significant difference between the two groups.

For the clay (%) variable, the range of values in the infected condition was between 9% and 45%, while in the uninfected condition, it ranged from 9% to 31%. The median clay (%) in the infected condition was higher at 13%, compared to 11% in the uninfected condition.

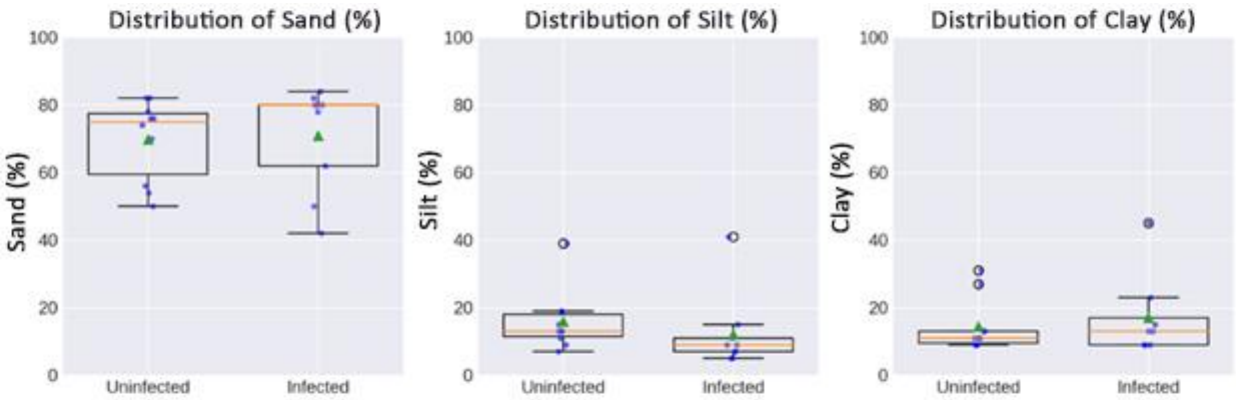


Figure 11. Distribution of sand, silt, and clay in *Ganoderma*-Infected and Uninfected Conditions

Table 4. Mean, median, minimum, maximum, standard error, and t-test values of soil physical variables.

Soil Physic Variables	Statistic	Uninfected	Infected	t Test
Sand (%)	Mean	69.80	70.90	ns
	Median	75.00	80.00	
	Minimum	50.00	42.00	
	Maximum	82.00	84.00	
	Standard Error	3.79	5.20	
Silt (%)	Mean	15.80	12.10	ns
	Median	13.00	9.00	
	Minimum	7.00	5.00	
	Maximum	39.00	41.00	
	Standard Error	2.85	3.76	
Clay (%)	Mean	14.40	17.00	ns
	Median	11.00	13.00	
	Minimum	9.00	9.00	
	Maximum	31.00	45.00	
	Standard Error	2.50	3.82	

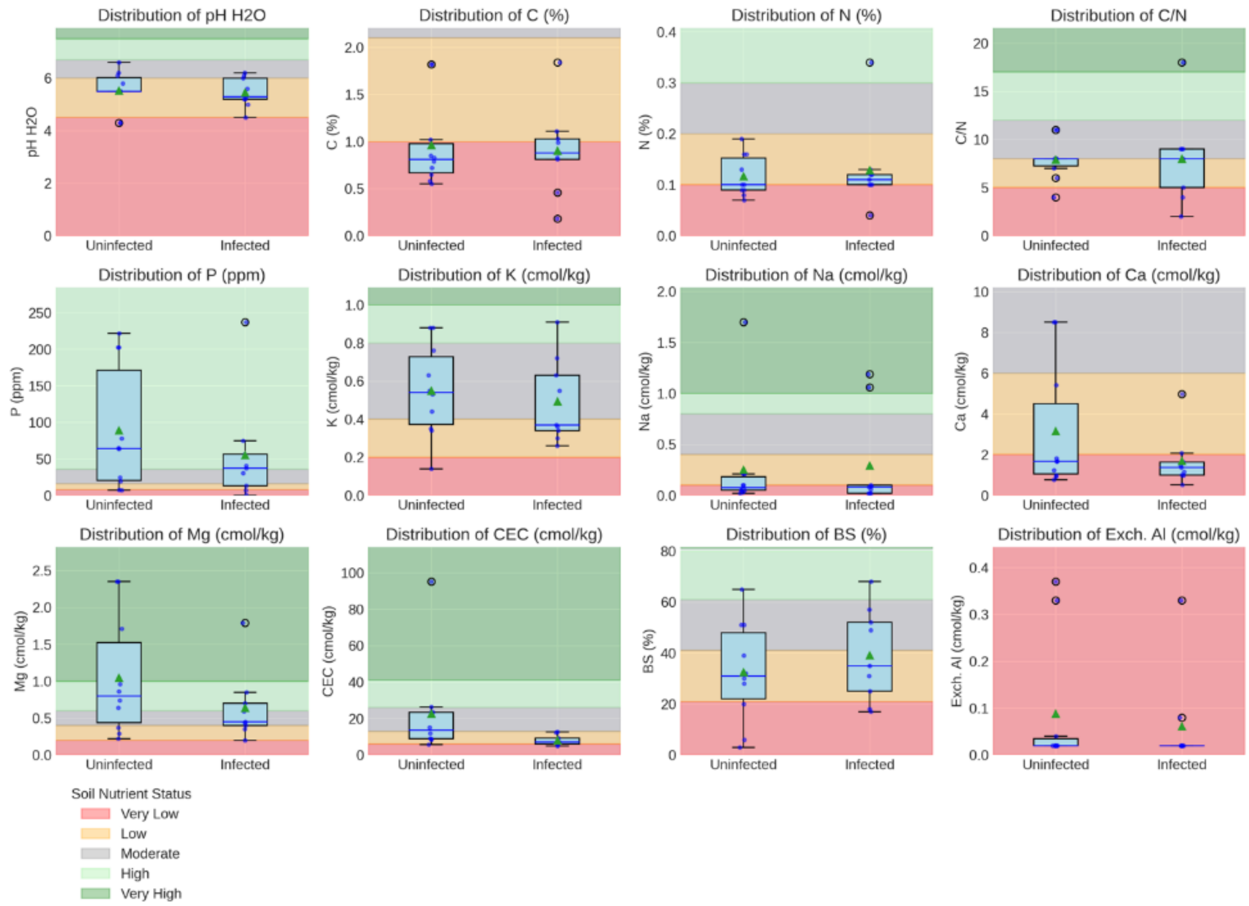
Notes: ns = not significant ($p \geq 0.05$), indicating that the difference between the Non-Infected and Infected groups is not statistically significant.

The mean clay (%) was also higher in the infected condition at 17.0 ± 3.82%, compared to 14.4 ± 2.50% in the uninfected condition. However, despite these differences, the t-test results indicated they were not statistically significant.

Figure 12 and Table 5 present boxplots of the distribution of three soil chemical properties. For the pH H_2O variable, the range of values in the infected condition was between 4.3 and 6.2, while in the uninfected condition, it ranged from 4.3 to 6.6. Although there is a slight difference in the range between the two conditions, the mean pH H_2O values indicate that both groups fall within the same low category. For the C (%) variable, the values in the infected condition ranged from 0.18% to 1.82%, whereas in the uninfected condition, they ranged from 0.55% to 1.82%. Despite a slight difference in the range, both conditions are categorized as very low, indicating that the soil in both conditions has low organic carbon content.

For the N (%) variable, the range of values in the infected condition was between 0.08% and 0.19%, while in the uninfected condition, it ranged from 0.07% to 0.18%. Both conditions fall into the low category, reflecting the low nitrogen content in the soil. For the C/N ratio, although the range of values between the infected and uninfected conditions differs, with 2 to 18 in the infected condition and 4 to 11 in the uninfected condition, both still fall within the low category. The uninfected condition showed higher values for the P (ppm) variable, with a mean of 89.17 ppm compared to 15.29 ppm in the infected condition. However, both conditions fall within the high category, indicating that the soil in both conditions has relatively high phosphorus availability.

For the Na (cmol kg^{-1}) variable, the values for both conditions are categorized as low, although there is some variation in the range of values. In the infected condition, Na values ranged from 0.02 to 1.19 cmol kg^{-1}, with a mean value of 0.29 cmol kg^{-1}. Meanwhile, in uninfected conditions, Na values ranged from 0.02 to 1.70 cmol kg^{-1}, with a mean value of 0.25 cmol kg^{-1}. For the Ca (cmol kg^{-1}) variable, the uninfected condition showed higher values with a mean of 3.15 cmol kg^{-1} compared to 1.69 cmol kg^{-1} in the infected condition, although both conditions remain in a low category. For the Mg (cmol kg^{-1}) variable, the uninfected condition showed higher values with a mean of 1.05 cmol kg^{-1}, categorized as very high. In contrast, the infected condition fell into the high category. For the Cation Exchange Capacity



Notes: Classification of soil chemical values as Very Low, Low, Moderate, High, or Very High is based on the soil fertility criteria outlined by PPKS (Adiwiganda, 1998).

Figure 12. Boxplot distributions of soil chemical properties comparing *Ganoderma*-infected and uninfected conditions.

Table 5. Mean, median, minimum, maximum, standard error, and t-test values of soil chemical variables between uninfected and *Ganoderma*-infected conditions.

Soil Chemical Variable	Statistic	Uninfected		Infected		t test
pH H_2O	Mean	5.53	Low	5.46	Low	ns
	Median	5.50		5.30		
	Minimum	4.30		4.50		
	Maximum	6.60		6.20		
	Standard Error	0.24		0.19		
Total Organic Carbon (C) (%)	Mean	0.96	Very Low	0.90	Very Low	ns
	Median	0.81		0.88		
	Minimum	0.55		0.18		
	Maximum	1.82		1.84		
	Standard Error	0.15		0.13		
Nitrogen (N) (%)	Mean	0.12	Low	0.13	Low	ns
	Median	0.10		0.11		
	Minimum	0.07		0.04		
	Maximum	0.19		0.34		
	Standard Error	0.01		0.02		
Carbon to Nitrogen Ratio (C/N)	Mean	7.90	Low	8.00	Low	ns
	Median	8.00		8.00		
	Minimum	4.00		2.00		
	Maximum	11.00		18.00		
	Standard Error	0.66		1.51		
Phosphorus (P) (ppm)	Mean	89.17	High	55.29	High	ns
	Median	64.70		37.25		
	Minimum	7.09		0.43		
	Maximum	221.69		237.24		
	Standard Error	27.32		24.08		
Potassium (K) (cmol kg^{-1})	Mean	0.55	Moderate	0.49	Moderate	ns
	Median	0.54		0.37		
	Minimum	0.14		0.26		
	Maximum	0.88		0.91		
	Standard Error	0.08		0.07		
Sodium (Na) (cmol kg^{-1})	Mean	0.25	Low	0.29	Low	ns
	Median	0.08		0.08		
	Minimum	0.02		0.02		
	Maximum	1.70		1.19		
	Standard Error	0.16		0.16		
Calcium (Ca) (cmol kg^{-1})	Mean	3.15	Low	1.69	Very Low	ns
	Median	1.67		1.37		
	Minimum	0.76		0.52		
	Maximum	8.51		4.97		
	Standard Error	0.99		0.44		
Magnesium (Mg) (cmol kg^{-1})	Mean	1.05	Very High	0.64	High	ns
	Median	0.80		0.45		
	Minimum	0.22		0.20		
	Maximum	2.35		1.79		
	Standard Error	0.26		0.16		
Cation Exchange Capacity (CEC) (cmol kg^{-1})	Mean	22.72	Moderate	8.02	Low	ns
	Median	13.53		7.09		
	Minimum	5.64		4.97		
	Maximum	95.12		12.66		
	Standard Error	8.37		0.64		
Base Saturation (BS) (%)	Mean	32.50	Low	39.11	Low	ns
	Median	31.00		35.00		
	Minimum	3.00		17.00		
	Maximum	65.00		68.00		
	Standard Error	6.27		6.05		
Exchangeable Aluminium (Al) (cmol kg^{-1})	Mean	0.09	Very Low	0.06	Very Low	ns
	Median	0.02		0.02		
	Minimum	0.02		0.02		
	Maximum	0.37		0.33		
	Standard Error	0.04		0.03		

Notes: Classification of soil chemical values as Very Low, Low, Moderate, High, or Very High is based on the soil fertility criteria outlined by PPKS (Adiwiganda, 1998).

(CEC) (cmol kg^{-1}) variable, the uninfected condition had overall higher values with a mean of 22.72 cmol kg^{-1} compared to 7.09 cmol kg^{-1} in the infected condition. This indicates a greater cation exchange capacity in the soil in uninfected conditions.

The Base Saturation (BS) (%) variable showed slightly higher values in the infected condition, with a mean of 35.00% compared to 32.50% in the uninfected condition, but both remained in the low category. For the Exchangeable Aluminium (cmol kg^{-1}) variable, both conditions exhibited shallow values, with a mean close to zero, indicating that the exchangeable aluminium content is minimal in the soil under both conditions. Overall, this analysis suggests that although soil chemical values vary between the infected and uninfected conditions, the t-test results indicate that these differences are not statistically significant (Table 5).

3.4. Root development

Based on the measurements of fresh and dry root weights (Fig. 13 & Table 6), there is a noticeable difference between uninfected and *Ganoderma*-infected palms. However, this difference is not statistically significant. For fresh root weight, uninfected palms had an average weight of 1203.57 ± 267.08 g, ranging from 35.00 g to 2995.00 g. In contrast, infected palms showed a lower average weight of 908.93 ± 247.33 g, ranging from 0.00 g to 2475 g. The median fresh root weight in uninfected palms was 995.00 g, significantly higher than 430 g in infected palms. A similar pattern was observed in dry root weight. Uninfected palms had an average dry root weight of 381.86 ± 75.85 g, ranging from 15.00 g to 825.00 g, while infected palms had an average dry root weight of 303.14 ± 85.61 g, ranging from 0.00 g to 1177.00 g. The median dry root weight also showed a difference, with uninfected palms having a median of 327.00 g compared to only 147.00 g in infected palms.

In infected palms, a value of 0.00 g was recorded for fresh and dry root weights (Table 6). According to the graph in Figure 13, this value was observed when sampling was conducted on oil palm trees with a mounding age of 3 months. At this stage, root development was minimal, with uninfected palms only reaching 35.00 g for fresh weight and 15.00 g for dry weight.

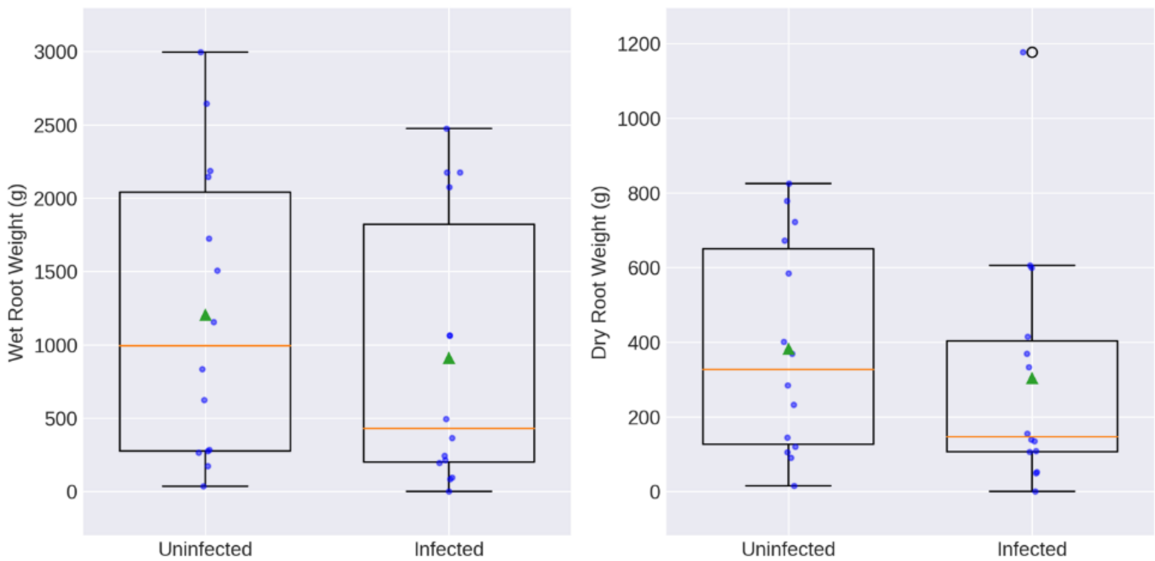


Figure 13. Boxplot of fresh and dry root weights in uninfected and infected.

Table 6. Mean, median, minimum, maximum, standard error, and t-test values for uninfected and infected fresh and dry root weights.

Variables	Statistic	Uninfected	Infected	t Test
Wet Root Weight (g)	Mean	1203.57	908.93	ns
	Median	995.00	430.00	
	Minimum	35.00	0.00	
	Maximum	2995.00	2475.00	
	Standard Error	267.08	247.33	
Dry Root Weight (g)	Mean	381.86	303.14	ns
	Median	327.00	147.00	
	Minimum	15.00	0.00	
	Maximum	825.00	1177.00	
	Standard Error	75.85	85.61	

Notes: * = significant ($p < 0.05$), indicating that the difference between the Non-Infected and Infected groups is statistically significant. ns = not significant ($p \geq 0.05$), indicating that the difference between the Non-Infected and Infected groups is not statistically significant.

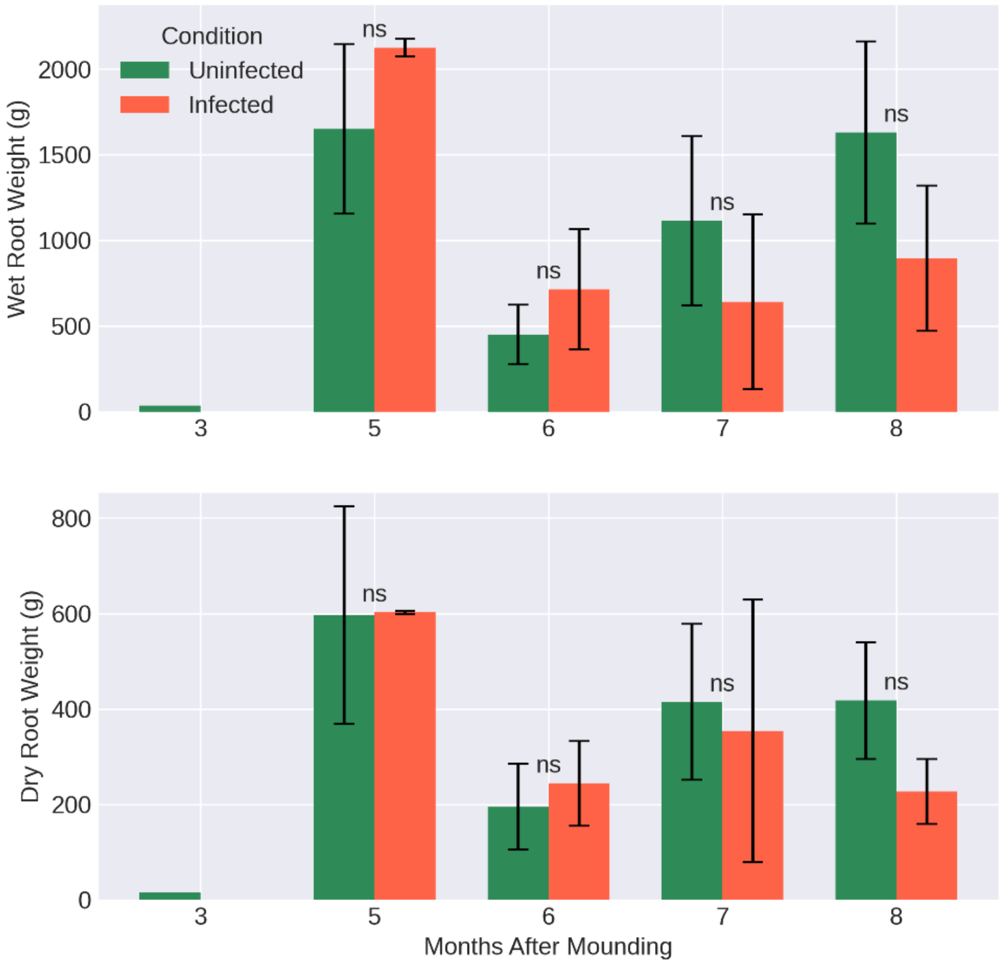


Figure 14. Fresh and dry root weights of *Ganoderma*-infected and uninfected palms at 3, 5, 6, 7, and 8 months after mounding.

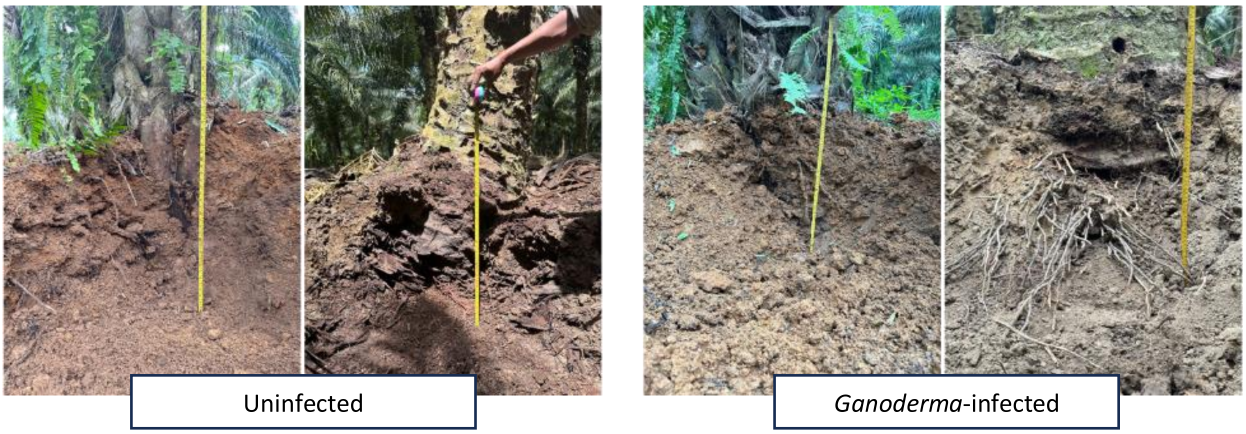


Figure 15. Root systems of uninfected (left) and *Ganoderma*-infected (right) palms.

Root development substantially increased by the fifth month, although the differences were not statistically significant. The average fresh root weight was 1,650 g in uninfected palms and 2,125 g in infected palms. Meanwhile, the average dry root weight was 597 g in uninfected palms and slightly higher at 602.5 g in infected palms. This indicates that the mounding process was quite effective in enhancing root area, mainly because the soil used for mounding was topsoil, which generally has high fertility. Interestingly, fresh and dry root weights were higher in *Ganoderma*-infected palms than in uninfected palms. This suggests that infected palms may have developed a robust defense mechanism, allowing them to survive and maintain functionality despite the stress caused by the infection.

Based on Figure 14, by the sixth month, root development had become more evident, with infected palms showing the highest average fresh root weight of 715 g, while uninfected palms had the lowest average fresh weight of 450 g. A similar pattern was observed for dry root weight, where infected palms had a dry weight of 244 g, compared to only 195 g in uninfected palms. This suggests that up to the sixth month, infected palms were still responding well to mounding, even outperforming uninfected palms, although the differences were not significant.

In the seventh and eighth months, uninfected palms' average fresh and dry root weights were higher than those of infected palms, although the differences were not significant. This indicates that uninfected palms were more effective at maintaining and expanding their root systems as the mounding age increased compared to infected palms. In the seventh month, the average fresh root weight in uninfected palms reached 1,115 g; in infected palms, it was only 642.5 g. The average dry root weight in uninfected palms was also higher at 414.75 g, compared to 354.25 g in infected palms. By the eighth month, this difference became even more pronounced. Uninfected palms had an average fresh root weight of 1,631 g, whereas infected palms had only 895 g. The dry root weight showed a similar trend, with uninfected palms having a dry weight of 417.6 g, compared to 226.8 g in infected palms (Fig. 15).

4. DISCUSSION

The interaction between soil texture, mounding practices, and root system dynamics in oil palm under both *Ganoderma-infected* and uninfected conditions revealed contrasting patterns of root development. Uninfected palms consistently developed more stable and extensive tertiary and quaternary roots, while infected palms exhibited fluctuating biomass, characterized by early compensatory growth that declined over time. These patterns reflect the combined influence of abiotic soil conditions, host physiological adjustments, and pathogen-host dynamics in shaping root system resilience.

Both infected and uninfected soils were classified as sandy loam according to the Soil Science Division Staff (2017) classification. Although statistical analysis revealed no significant differences in the proportions of sand, silt, and clay, there was a consistent trend where uninfected palms had higher sand and silt content and lower clay content. This observation aligns with previous studies, which demonstrated that sandy soils, with their high porosity and low organic matter content, facilitate *Ganoderma* colonization (Lisnawita et al., 2016; Susanto et al., 2013; Utami et al., 2016). These soils often possess low cation exchange capacity (CEC) and poor water-holding capacity, conditions that exacerbate abiotic stress and predispose palms to pathogen invasion (Ayundra et al., 2022). In such vulnerable soil environments, the lack of buffering capacity may contribute to physiological instability in infected palms, particularly in sustaining root development under biotic stress.

Three months after mounding, root biomass development in *Ganoderma*-infected oil palms remained minimal, indicating that root initiation had not yet been actively established or was inhibited during the early stage of infection. By the fifth month, a marked increase was observed, with infected palms showing higher average wet and dry root weights than uninfected palms, although the difference was not statistically significant. However, from the sixth to the eighth month, root biomass in infected palms declined once again, whereas uninfected palms maintained relatively stable root growth throughout the observation period. This cross-sectional pattern suggests a short-term compensatory mechanism in infected palms, likely triggered by early defense responses such as lignification and the activation of pathogenesis-related genes, alongside temporary metabolic adjustments intended to preserve root function (Bahari et al., 2018; Faizah et al., 2022; Nugroho et al., 2025). Nevertheless, the subsequent reduction in root biomass indicates that such physiological compensation imposes a high metabolic cost and is ultimately insufficient to sustain root system resilience under continuous pathogen pressure. These observations are consistent with previous findings. Hushiarian et al. (2013) reported a gradual decline in defense-related enzyme activity during the progression of *Ganoderma* infection, while Nusaibah and Musa (2019) documented systemic physiological dysfunction and the accumulation of phytotoxic compounds in infected root tissues. Both factors contribute to declining root vitality and illustrate the limitations of short-term defense activation as a sustainable survival strategy. These insights underscore the importance of reinforcing long-term physiological support to maintain root system integrity in chronically infected palms. It is important to note that root biomass measurements at each time point were obtained from different palm trees, due to the destructive nature of root sampling. As a result, the temporal patterns discussed here represent population-level dynamics rather than longitudinal changes within the same individuals.

From an anatomical perspective, uninfected palms developed abundant tertiary and quaternary roots, which are structurally optimized for water and nutrient absorption due to their increased surface area and density of root hairs. In contrast, infected palms showed reduced development of these fine roots and instead produced thicker, primary-like roots whose primary function appears to shift toward structural support. Supena et al. (2024) suggested that such morphological adaptations may enhance stability in stressed palms, but the trade-off is reduced efficiency in nutrient uptake. This structural-functional compromise may contribute to the observed stunting and leaf chlorosis in infected palms.

Mounding practices played a pivotal role in modifying root system responses across both groups. Priwiratama et al. (2014) found that mounding delayed visible *Ganoderma* symptoms by up to one year, likely due to the physical and biological advantages it confers. The additional soil mass increases rooting volume, particularly in inter-row areas enriched with decomposed organic matter like pruned fronds and empty fruit bunches (Priwiratama et al., 2020; Sari, 2015). Suwardi et al. (2022) demonstrated that mounded zones retained more moisture, thereby enhancing root proliferation and microbial activity. Furthermore, Kheng et al. (2013) reported that bacterial colony-forming units increased by approximately 1.3-fold in mounded soils, suggesting potential benefits to rhizosphere health and plant immunity.

These physical enhancements are further mediated by hormonal signaling. Studies have shown that salicylic acid (SA), jasmonic acid (JA), and ethylene (ET) pathways are activated during *Ganoderma* infection (Ho & Tan, 2015; Karunarathna et al., 2024). These phytohormones regulate lignification, root elongation, and defense-related gene expression. Faizah et al. (2022) found that increased SA levels were positively correlated with early root biomass recovery, suggesting its role in short-term defense. However, prolonged activation of these pathways may divert metabolic resources away from vegetative growth toward sustained defense, potentially explaining the subsequent biomass decline in infected palms. This reallocation of energy reflects a physiological trade-off that compromises root system longevity.

Rhizosphere microbiome dynamics also represent a critical but underexplored component of root system stability. Nusaibah and Musa (2019) and Shokrollahi et al. (2023) emphasized the role of hormone–microbiome interactions in modulating host immunity. Beneficial microbes such as *Trichoderma* spp. Not only promote root development, but it also stimulates systemic acquired resistance. The increase in microbial CFU in mounded plots, as observed in this study, suggests an environment conducive to beneficial microbial colonization. However, in the presence of a dominant pathogen such as *Ganoderma*, rhizosphere equilibrium may be disrupted, thereby reducing the effectiveness of mutualistic plant–microbe interactions.

While the present findings offer valuable insights into the physiological and environmental mechanisms influencing root development under pathogen stress, several limitations must be acknowledged. First, the observation period of eight months may be insufficient to capture the full temporal dynamics of root system deterioration or recovery, especially in chronic disease conditions. Second, this study did not incorporate direct quantification of phytohormonal concentrations or microbial community structure. Consequently, interpretations involving hormone signaling and rhizosphere dynamics remain inferential, based on secondary literature rather than empirical evidence. Third, uncontrolled environmental factors such as rainfall, temperature, and humidity may have introduced variability into root development patterns.

To address these limitations, future research should integrate molecular and metagenomic techniques to measure key signaling molecules such as SA, JA, and ET, and to profile the composition and functional roles of rhizosphere microbiomes. Long-term field trials across multiple locations with varying soil types are also necessary to evaluate the sustained impact of mounding practices under diverse edaphic and environmental conditions. Moreover, the potential synergy between mounding and biological interventions, such as bioaugmentation with Trichoderma, Bacillus, or arbuscular mycorrhizal fungi (AMF), should be explored. These strategies, when combined with organic amendments, may offer a holistic and ecologically sound framework for enhancing root system resilience and suppressing *Ganoderma* progression across diverse soil and climatic contexts. This study is limited by its observation period, which focuses only on the early to mid-stages of infection, and it does not directly assess hormonal responses or rhizosphere microbiome dynamics. Future research should investigate the long-term impact of mounding on nutrient cycling, hormone signaling (such as salicylic acid and jasmonate), and beneficial microbial interactions. Integrating physiological and microbiological approaches will provide a more holistic understanding of sustainable oil palm cultivation under *Ganoderma* stress.

5. CONCLUSION

This study revealed that *Ganoderma*-infected palms have a root development system with biomass nearly comparable to that of uninfected palms. However, in the seventh and eighth months after mounding, the root biomass development in infected palms is less extensive than in uninfected palms. Functionally, many samples of infected palms exhibited the growth of primary roots on the mounded stems. Although crucial for supporting the plant structure, these primary roots are less effective in nutrient absorption than the more developed tertiary and quaternary roots found in uninfected palms. Consequently, *Ganoderma*-infected palms experience impaired nutrient uptake, ultimately leading to reduced plant health and productivity, as evidenced by suppressed vegetative growth, particularly reflected in decreased chlorophyll content. However, the growth of these primary roots on the mounded stems is also critical for extending the lifespan of the infected palms. The environmental conditions surrounding the root system, such as cation exchange capacity (CEC) and magnesium (Mg) content, also significantly support plant health. In uninfected palms, CEC and magnesium nutrient status are generally higher, allowing the soil to retain and supply essential cations more effectively.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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