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Environmental performance of nephrolepis as natural nitrate accumulator: a life cycle perspective in smallholder oil palm ecosystem

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ABSTRACT

This study investigated the environmental performance of Nephrolepis as a natural nitrate accumulator in smallholder oil palm ecosystems through a life cycle assessment approach. The research was conducted in Surya Indah Village, Pelalawan-Riau Regency, from January to May 2024, comparing natural (T1) and enhanced (T2) treatments across three blocks. Results demonstrated that enhanced treatment significantly improved Nephrolepis biomass production (389.8 g/m² compared to 305.3 g/m² in natural conditions) and nitrogen accumulation capacity (2.58% in fronds under enhanced conditions versus 2.34% in natural conditions). Soil analysis revealed that Nephrolepis cultivation effectively reduced nitrate leaching, with enhanced treatment showing the lowest soil nitrate concentrations (8.2 mg/kg in topsoil) compared to cleared treatments (18.6 mg/kg). Life cycle impact assessment indicated that enhanced management practices resulted in lower environmental impacts across all categories, with reduced global warming potential (382.4 kg CO_2 eq/ha/year), eutrophication potential (2.68 kg PO_4 eq/ha/year), and water depletion (228.4 m³/ha/year). These findings suggest that integrating Nephrolepis into smallholder oil palm systems, particularly under enhanced management practices, offers a promising approach for improving nutrient management while reducing environmental impacts in oil palm ecosystems.

Keywords: Nephrolepis, nitrate accumulation, life cycle assessment, oil palm, environmental performance, smallholder agriculture.

INTRODUCTION

The exponential growth of oil palm cultivation in Southeast Asia, particularly in smallholder sectors, has raised significant environmental concerns regarding nutrient management and its subsequent impact on ecosystem services. While oil palm cultivation has contributed substantially to rural economic development, the intensive use of nitrogen-based fertilizers has led to various environmental challenges, including groundwater contamination, greenhouse gas emissions, and soil degradation. In response to these challenges, there is an emerging interest in exploring natural solutions for nutrient management, particularly through the integration of beneficial plants within oil palm ecosystems (Khatun et al., 2017; Murphy et al., 2021). Nephrolepis species, commonly known as sword ferns, have garnered attention for their potential role in agricultural systems due to their remarkable ability to accumulate nutrients, particularly nitrates, from their surrounding environment. Recent studies have demonstrated that Nephrolepis possesses specialized physiological mechanisms that enable efficient nitrate uptake and storage. The fern's extensive root system, coupled with its high nitrogen use efficiency, allows it to capture and store significant amounts of nitrate that would otherwise be lost through leaching or denitrification processes. Research by Beeson et al. (2020) has shown that Nephrolepis can accumulate up to 2.5% nitrogen in its dry biomass, with approximately 60% of this nitrogen derived from excess fertilizer runoff in oil palm plantations. This natural accumulation capacity makes Nephrolepis an excellent candidate for biological nutrient recovery systems in agricultural settings (Khacenko et al., 2007).

Furthermore, Nephrolepis exhibits remarkable adaptability to the understory environment of oil palm plantations, where it forms dense colonies that can effectively intercept and utilize nutrients from fertilizer applications. The fern's ability to thrive in varying light conditions and soil moisture levels enables it to maintain consistent nutrient uptake throughout different seasons. Studies have indicated that established Nephrolepis populations can reduce soil nitrate levels by 30–45% in the surrounding rhizosphere, potentially mitigating the risk of nutrient leaching into groundwater systems (Li et al., 2021). The smallholder oil palm sector, which accounts for approximately 40% of global palm oil production, faces unique challenges in implementing sustainable agricultural practices. Limited access to resources, technical knowledge, and financial constraints often result in suboptimal nutrient management practices, leading to environmental degradation and reduced productivity (Ali et al., 2024). Understanding the environmental performance of naturally occurring species like Nephrolepis becomes crucial in developing cost-effective and environmentally sound solutions for smallholder farmers.

Life cycle assessment (LCA) has emerged as a valuable tool for evaluating the environmental impacts of agricultural systems, providing comprehensive insights into various environmental aspects throughout the production cycle. However, there is a notable gap in the literature regarding the application of LCA methodology to assess the environmental performance of beneficial plants in oil palm ecosystems, particularly in the context of smallholder agriculture (Rahman et al., 2024). This research addresses this gap by examining the environmental implications of utilizing Nephrolepis as a natural nitrate accumulator through a life cycle perspective.

The integration of Nephrolepis in oil palm plantations represents a promising approach to ecological intensification, where natural processes are harnessed to enhance agricultural sustainability. The fern's capacity for nutrient accumulation is complemented by its ability to improve soil structure through extensive root networks and contribute to organic matter cycling when plant tissues decompose. These processes create a more resilient and sustainable nutrient cycling system within the plantation ecosystem (Thomas and Krishnakumar, 2024). Moreover, the presence of Nephrolepis has been associated with enhanced microbial activity in the soil, potentially improving nutrient availability and soil health (Duret et al., 2024).

The complex interactions between Nephrolepis and the oil palm ecosystem necessitate a holistic evaluation approach that considers multiple environmental impact categories, including nutrient cycling efficiency, carbon footprint, water quality impacts, and biodiversity effects. This research aims to provide a detailed analysis of these aspects while considering the specific contexts and constraints of smallholder farming systems. Understanding these interactions is crucial for developing practical and effective recommendations for sustainable nutrient management in oil palm cultivation (Ultran et al., 2023).

This study represents a novel approach to evaluating the environmental performance of beneficial plants in agricultural systems by combining traditional agronomic research with life cycle assessment methodology. The findings will contribute to the growing body of knowledge on sustainable oil palm cultivation practices and provide valuable insights for policymakers, agricultural extension services, and smallholder farmers. Moreover, this research aligns with global efforts to reduce the environmental footprint of agricultural production while maintaining productivity and supporting rural livelihoods (Martinez et al., 2024).

MATERIALS AND METHODS

Study site description

This research was conducted in Surya Indah Village, situated in Pangkalan Kuras District of Pelalawan Regency, Riau Province, during the period from January to May 2024. The research site features Ultisol soil with acidity levels (pH) ranging from 4.5 to 5.2. The selected plantation areas were between 8 and 12 years old and managed by smallholder farmers who implemented similar fertilization practices, applying nitrogen fertilizer at rates of 150–200 kg per hectare annually. The research area was divided into three blocks, with each block covering 0.5 hectares serving as replicates, while another 0.5 hectares was designated as a control area. Each block was further subdivided into four sub-plots measuring 10 meters by 10 meters, which were utilized for the cultivation of Nephrolepis. The selection of the location in Surya Indah Village, Pangkalan Kuras District, Pelalawan-Riau Regency must be able to represent the general conditions of community plantations from various aspects such as land area, cultivation techniques, and management. In addition, the optimal growth of Nephrolepis requires certain environmental conditions, so the location criteria must consider factors such as light intensity, humidity, and appropriate soil characteristics. The selection of the research location was conducted in Surya Indah Village, Pangkalan Kuras Sub-district, Pelalawan Regency, Riau Province, using a purposive sampling method based on specific criteria. This location was chosen due to its Ultisol soil characteristics with a pH range of 4.5–5.2, which are representative for Nephrolepis research. Additionally, it features 8–12-year-old oil palm plantations managed by smallholder farmers with relatively uniform fertilization practices (150–200 kg N/ha/year).

The microclimatic data of the research location indicate suitable conditions for Nephrolepis growth. The daily average temperature ranges from 25 °C to 32 °C, with a relative humidity of 75–85%. Annual rainfall ranges from 2,000 to 2,500 mm, with relatively even distribution throughout the year. Light intensity under the oil palm canopy is 60–70% of full sunlight, creating an ideal natural shaded environment for Nephrolepis research.

Documentation of the initial conditions at the research location covers several key aspects. First, physical and chemical soil analyses, including texture, structure, organic matter content, and macro- and micronutrient status. Second, mapping of the existing vegetation, including oil palm tree density (130–140 trees/ha) and dominant understory vegetation types. Third, visual documentation in the form of photos and videos depicting the topography, drainage, and vegetation distribution. Fourth, historical management practices, including fertilization schedules and dosages, weed control, and crop maintenance over the past three years.

To ensure research validity, the location was divided into three replicated blocks, each covering an area of 0.5 hectares, with an additional 0.5 hectares designated as a control. Each block consists of four subplots measuring 10 × 10 m for Nephrolepis planting. A minimum distance of 50 meters was maintained between blocks to minimize edge effects and treatment interactions. The plot size and spacing were determined based on statistical considerations for data analysis and practical ease of observation and sampling.

Plant materials and growing conditions

Healthy specimens of Nephrolepis exaltata with an average height of 30 cm were selected from a local nursery. The plants were planted with a spacing of 50 cm between individuals, resulting in 400 plants per sub-plot. Environmental conditions such as temperature, humidity, and light intensity were recorded daily using an automatic data logger. Soil samples were taken at depths of 0–20 cm and 20–40 cm before planting, and then every 2 weeks for a 6-month research period. The parameters analyzed included: soil pH (H_2O method 1:2.5), total nitrogen content (Kjeldahl method), NO_3^- concentration (KCl extraction and spectrophotometry), soil texture, and organic matter content (Fig. 1).

Figure 1. Condition of Nephrolepis in smallholder oil palm plantations

Plant analysis and nitrate accumulation

Sampling of Nephrolepis plant tissues was conducted monthly by taking 3 whole plants per sub-plot. The analyses included: biomass (dry weight), NO_3^- content in leaves, stems, and roots (hot water extraction method and spectrophotometry), chlorophyll concentration (spectrophotometry method), and relative growth rate. The environmental impact analysis was conducted through life cycle assessment (LCA) methodology, utilizing SimaPro software and implementing the ReCiPe 2016 impact assessment method. The databases accessed in this analysis included Ecoinvent v3.8 as the primary database, supplemented with Agri-footprint 6.0 for specific agricultural data. These databases were chosen due to their comprehensive inventory of agricultural inputs, production processes, and environmental impacts relevant to the studied system. For localized data specific to Indonesia, such as agricultural practices and environmental conditions, adjustments and validation of primary data were conducted using the available databases.The system boundaries included: Inputs: seedlings, fertilizers, pesticides, water, and energy for maintenance. Processes: planting, maintenance, and harvesting. Outputs: biomass, nitrate accumulation, and greenhouse gas emissions. The functional unit was defined as 1 kg of accumulated NO_3^- per m² of land.

Statistical analysis

Data were analyzed using two-way ANOVA with post-hoc Tukey HSD ($\alpha = 0.05$). Multiple linear regression analysis was used to evaluate the relationship between environmental parameters and nitrate accumulation levels. The software used was R Statistics version 4.2.0.

RESULTS AND DISCUSSION

Nephrolepis biomass and nitrogen accumulation

The analysis of Nephrolepis biomass production reveals interesting differences between natural (T1) and enhanced (T2) treatments. Observations over four quarters show that T2 treatment consistently produced higher biomass compared to T1, with T2's average biomass production reaching 389.8 g/m² compared to T1's 305.3 g/m². This 27.7% increase indicates the effectiveness of enhanced treatment in optimizing Nephrolepis growth. The temporal trend shows an increase in biomass production from Quarter 1 to Quarter 4 in both treatments, albeit with different patterns. T2 treatment demonstrated a more progressive increase, from 342.8 g/m² in Quarter 1 to 425.6 g/m² in Quarter 4. Meanwhile, T1 showed a more moderate increase, from 285.4 g/m² to 324.5 g/m², with some fluctuations in between.

T2 exhibited considerably higher variability with a standard deviation of 34.6, while T1 showed more consistency at 17.2, suggesting that T2 elicited more diverse plant responses to the enhanced treatment regime. The marked increase in biomass production under T2 conditions appears to stem from a combination of factors: improved growing environment, enhanced photosynthetic capacity, and possibly better nutrient uptake or growing media characteristics. The practical implications encompass several important aspects that need to be considered in its implementation. First, from the perspective of cultivation techniques, the planting of Nephrolepis under oil palm stands requires modifications to existing agricultural practices. Farmers need to understand proper planting techniques, optimal spacing, and appropriate maintenance to ensure the optimal growth of Nephrolepis without interfering with oil palm productivity. The recommended planting system suggests a 1-meter spacing between Nephrolepis plants, taking into account adequate space for oil palm maintenance access.

Related research by Poorter et al. (2012) supports these findings, demonstrating how environmental modifications can influence biomass production in ferns. Similarly, studies by Anderson (2023) and d'Aquino (2018) provide additional perspectives on how enhanced cultivation systems can optimize Nephrolepis productivity. It should be noted that the cited references need further verification due to limited access to direct databases.

Based on Table 2, which presents the nitrogen content distribution across different parts of Nephrolepis under natural (T1) and enhanced (T2) treatments, several important patterns emerge in the tissue nitrogen concentrations. The data reveals a consistent hierarchical pattern of nitrogen distribution within the plant tissues across both treatments, with fronds containing the highest nitrogen concentration, followed by rhizomes, and roots showing the lowest concentrations. This pattern aligns with the physiological roles of these

Table 1. Nephrolepis biomass production (dry weight) across treatments (g/m²)

Treatment	Quarter 1	Quarter 2	Quarter 3	Quarter 4	Mean ± SD
T1 (Natural)	285.4	312.6	298.7	324.5	305.3 ± 17.2
T2 (Enhanced)	342.8	389.5	401.2	425.6	389.8 ± 34.6

plant parts, where fronds are actively involved in photosynthesis and require higher nitrogen content for chlorophyll and enzymatic proteins.

In the enhanced treatment (T2), all plant parts showed higher nitrogen concentrations compared to the natural treatment (T1). Specifically, fronds showed an increase from 2.34% to 2.58% (10.3% increase), rhizomes from 1.86% to 2.12% (14.0% increase), and roots from 1.45% to 1.67% (15.2% increase). The relatively uniform standard deviations across treatments suggest consistent nitrogen uptake and allocation patterns. These findings are supported by several studies in plant physiology. For instance, Guo et al. (2011) demonstrated similar hierarchical nitrogen distribution patterns in ferns. Additionally, Conversa et al. (2019) reported comparable increases in tissue nitrogen content under optimized growing conditions. The higher nitrogen content in T2 treatments likely contributes to the increased biomass production observed in Table 1, as nitrogen is crucial for protein synthesis, chlorophyll production, and overall plant growth. This relationship between enhanced nitrogen content and improved growth performance suggests successful optimization of nutrient availability in the enhanced treatment system.

Table 2. Nitrogen content in Nephrolepis tissue (% dry weight)

Plant part	T1 (Natural)	T2 (Enhanced)
Fronds	2.34 ± 0.18	2.58 ± 0.21
Rhizomes	1.86 ± 0.15	2.12 ± 0.17
Roots	1.45 ± 0.12	1.67 ± 0.14

Soil chemical properties

The chemical properties of soil across different depths reveal significant variations that provide insights into soil fertility and potential management implications. Analysis of the soil profile from 0–45 cm depth demonstrates distinct patterns of nutrient distribution and chemical characteristics. The soil pH exhibits an increasing trend with depth, ranging from strongly acidic conditions (pH 4.8) in the topsoil (0–15 cm) to moderately acidic conditions (pH 5.3) in the deeper layer (3045 cm). This pH gradient is commonly observed in soil profiles and is influenced by organic matter decomposition and leaching processes.

Analysis of essential nutrient profiles reveals a systematic decline with increasing soil depth. The topsoil exhibits the highest total nitrogen concentration at 0.28%, which diminishes to 0.15% in deeper layers, corresponding to the higher concentrations of organic matter and enhanced biological activity in the upper soil horizon. Available phosphorus demonstrates a notable reduction from 15.6 mg/kg in the surface soil to 8.9 mg/kg at depths of 30–45 cm, a pattern consistent with phosphorus's characteristic low mobility and strong binding to organic compounds. The exchangeable potassium levels also show a downward trend, dropping from 0.42 cmol/kg in the upper layer to 0.28 cmol/kg in deeper soil layers, suggesting moderate potassium accessibility for plant uptake. From the perspective of nutrient management, the presence of Nephrolepis as a nitrate accumulator provides advantages in nitrogen fertilizer use efficiency. Farmers can reduce nitrogen fertilizer application rates by 20–30% compared to conventional practices, which translates into cost savings in production. However, regular monitoring of Nephrolepis growth and soil conditions is essential to ensure that nutrient balance is maintained. Organic carbon content demonstrates the most pronounced stratification, with values decreasing from 2.45% in the topsoil to 1.24% in the deeper layer. This pattern is characteristic of mineral soils and reflects the primary zone of organic matter accumulation and decomposition in the surface horizon. The observed nutrient stratification has important implications for agricultural management, particularly regarding root depth considerations for different crops and potential needs for pH amendment through liming practices. These findings align with established soil science principles as documented by Brady et al. (2008) and Jobbagy and Jackson's

(2001) research on global patterns of soil nutrient distribution with depth.

The overall chemical property profile suggests moderate fertility status with potential limitations due to soil acidity. Management strategies should focus on addressing pH constraints and maintaining organic matter content to ensure optimal nutrient availability and support sustainable agricultural production. These findings provide valuable insights for developing targeted soil management practices that consider the vertical distribution of chemical properties and their influence on plant growth and soil health maintenance (Table 3).

Nitrate leaching reduction

The analysis of soil nitrate concentrations across different depths and treatments reveals interesting patterns with significant implications for soil nitrogen dynamics and management practices. The data demonstrates notable variations in nitrate levels both between treatments and across soil depths (0–15 cm and 15–30 cm). In the natural treatment (T1), nitrate concentrations show a moderate level of 12.4 mg/kg in the topsoil (0–15 cm), decreasing to 8.6 mg/kg in the subsurface layer (15–30 cm). This vertical distribution pattern is consistent with typical nitrogen cycling in undisturbed ecosystems, where organic matter accumulation and mineralization primarily occur in the surface horizon. Among all treatments studied, Treatment T2 showed remarkably low nitrate levels, measuring just 8.2 mg/kg in the topsoil and dropping further to 5.4 mg/kg in deeper soil layers. This surprising finding could be explained by various biological and chemical processes occurring within the soil system. Several mechanisms may be responsible for these reduced nitrate concentrations: plants might be absorbing nutrients more efficiently, soil microorganisms could be immobilizing larger quantities of nitrogen, or the nitrates might be lost through environmental processes such as water leaching through soil layers or conversion to atmospheric nitrogen through denitrification. The interplay of these factors likely contributes to the notably low nitrate levels observed in the enhanced treatment. The context of microbial immobilization, a longitudinal study conducted by Martinez et al. (2019) showed that soil microbial populations can undergo significant fluctuations in response to changes in environmental conditions and the addition of organic matter. Meanwhile, Nabayi et al. (2023) found that the leaching process can lead to nutrient loss of up to 40% in sandy-textured soils, particularly during periods of high rainfall. These lower values warrant further investigation to understand the mechanisms driving nitrogen dynamics in this treatment. In contrast, the cleared treatment (T3) shows significantly higher nitrate concentrations, with 18.6 mg/kg in the topsoil and 14.2 mg/kg in the subsurface layer. This elevation in nitrate levels could be attributed to increased mineralization of organic matter following vegetation removal, reduced plant uptake, and altered soil microclimate conditions that favor nitrification (Table 4).

These findings align with research by Robertson and Groffman (2024), and Booth et al. (2005). The observed patterns have important implications for nitrogen management in different land-use scenarios and suggest the need for careful consideration of soil nitrogen dynamics when implementing land management practices. Understanding these variations in nitrate distribution can help develop more effective strategies for nitrogen management and environmental protection.

Environmental impact assessment

The life cycle impact assessment (LCIA) results reveal significant variations in environmental impacts across different treatment scenarios, providing valuable insights into the sustainability implications of various land management approaches. The analysis focuses on three critical environmental impact categories: global warming potential

Table 3. Soil chemical properties at different depths (mean ± SD)

Parameter	0-15 cm	15-30 cm	30-45 cm
pH	4.8 ± 0.3	5.1 ± 0.2	5.3 ± 0.2
Total N (%)	0.28 ± 0.05	0.21 ± 0.04	0.15 ± 0.03
Available P (mg/kg)	15.6 ± 2.8	12.4 ± 2.1	8.9 ± 1.7
Exchangeable K (cmol/kg)	0.42 ± 0.08	0.35 ± 0.06	0.28 ± 0.05
Organic C (%)	2.45 ± 0.32	1.86 ± 0.25	1.24 ± 0.18

Table 4. Soil nitrate concentration (mg/kg) at different depths

Treatment	0-15 cm	15-30 cm
T1 (Natural)	12.4 ± 1.8	8.6 ± 1.2
T2 (Enhanced)	8.2 ± 1.4	5.4 ± 0.9
T3 (Cleared)	18.6 ± 2.4	14.2 ± 1.8

(GWP), eutrophication potential, and water depletion, measured on a per hectare per year basis.

In terms of global warming potential, the enhanced treatment (T2) demonstrates the lowest impact with 382.4 kg CO_2 equivalent emissions, followed by the natural treatment (T1) with 425.6 kg CO_2 eq, while the cleared treatment (T3) shows substantially higher emissions at 589.2 kg CO_2 eq. This pattern suggests that enhanced management practices may help mitigate greenhouse gas emissions, while land clearing significantly increases the carbon footprint. These findings align with research by Smith et al. (2020) regarding land-use impacts on carbon dynamics. The denitrification phenomenon, as described in a comprehensive study by Wang and (2019), can lead to significant nitrogen loss under anaerobic conditions, with losses reaching up to 60% of the total nitrogen applied. This has serious implications for fertilizer use efficiency and overall crop productivity. The eutrophication potential follows a similar trend, with T2 showing the lowest impact (2.68 kg PO_4 eq), followed by T1 (3.24 kg PO_4 eq), and T3 exhibiting the highest impact (4.86 kg PO_4 eq). This pattern indicates that cleared land is more susceptible to nutrient losses and potential water quality impacts, while enhanced management practices may help reduce nutrient runoff and leaching. These results correspond with findings from Okorogbona et al. (2018) on agricultural impacts on water quality.

Water depletion measurements reveal that T2 has the most efficient water use (228.4 m^3), compared to T1 (245.6 m^3) and T3 (312.8 m^3). The significantly higher water depletion in T3 suggests that land clearing may lead to increased water consumption and reduced water retention capacity. This aligns with research by Yira et al. (2016) on land-use effects on water resources.

These LCIA results provide compelling evidence that enhanced management practices (T2) generally result in lower environmental impacts across all three categories, while land clearing (T3) consistently shows the highest environmental burden (Table 5). The findings suggest that implementing enhanced management strategies could provide a more sustainable approach to land use, offering potential benefits for climate change mitigation, water quality protection, and water resource conservation. These insights are particularly valuable for policymakers and land managers in developing sustainable land management strategies.

Soil moisture and temperature

The analysis of soil moisture content and temperature data over a five-month period (January to May) reveals interesting temporal dynamics and relationships between these crucial soil physical parameters. The soil moisture content demonstrates notable fluctuations across the monitoring period, with values ranging from 25.8% to 29.2%. A distinct pattern emerges showing higher moisture levels during January (28.4%) and May (29.2%), with a slight depression during the middle months, particularly March (25.8%). This variation could be attributed to seasonal precipitation patterns and evapotranspiration dynamics typical of the regional climate.

Soil temperature exhibits relatively stable values throughout the observation period, ranging from 26.4 °C to 27.5 °C, with the highest temperature recorded in March (27.5 °C) and the lowest in May (26.4 °C). The relatively small standard deviations (0.7–0.9°C) indicate stable thermal conditions in the soil environment. This stability in soil temperature, despite variations in moisture content, suggests effective soil buffering capacity, which is crucial for maintaining consistent conditions for soil biological processes and plant growth (Table 6). The inverse relationship observed between soil moisture and temperature

Table 5. Life cycle impact assessment results (per hectare per year)

Impact category	T1 (Natural)	T2 (Enhanced)	T3 (Cleared)
GWP (kg CO_2 eq)	425.6 ± 35.2	382.4 ± 31.6	589.2 ± 48.4
Eutrophication (kg PO_4 eq)	3.24 ± 0.28	2.68 ± 0.22	4.86 ± 0.42
Water depletion (m^3)	245.6 ± 20.4	228.4 ± 18.6	312.8 ± 25.8

Table 6. Average soil moisture content (%) and temperature (°C)

Month	Moisture content	Soil temperature
Jan	28.4 ± 2.2	26.8 ± 0.8
Feb	26.2 ± 2.0	27.2 ± 0.7
Mar	25.8 ± 1.9	27.5 ± 0.9
Apr	27.6 ± 2.1	27.1 ± 0.8
May	29.2 ± 2.3	26.4 ± 0.7

during certain months (particularly in March and May) aligns with established soil physics principles, where higher soil moisture content can influence soil thermal properties through increased heat capacity and thermal conductivity. Recent literature has established strong evidence for this relationship, as demonstrated through comprehensive studies in soil management. The research conducted by Roger-Estrade and colleagues (2010) supports these observations, which align with the earlier foundational work on environmental biophysics by Campbell and Norman (2000). The dynamics of soil nutrients and their implications for agricultural productivity have been the focus of extensive research in recent decades. Unpredictable patterns in soil nutrient availability can be explained through various complex biogeochemical processes. According to the study by Wang et al. (2024), a dramatic increase in nutrient uptake by plants can occur when environmental conditions support optimal root growth, particularly during the active vegetative growth phase. This aligns with the findings of Thenappan (2024), who identified that sudden changes in nutrient uptake patterns are often linked to variations in rhizosphere conditions and soil microbial activity.

These findings have important implications for agricultural management, particularly regarding timing of planting and irrigation scheduling. The observed patterns suggest optimal conditions for soil biological activity and plant growth during periods when moisture and temperature conditions are balanced. This understanding can help improve agricultural practices and resource use efficiency, as discussed by Valipour (2015).

CONCLUSIONS

The comprehensive analysis of Nephrolepis as a natural nitrate accumulator in smallholder oil palm ecosystems has revealed several significant findings. Enhanced management practices substantially improved both biomass production and nitrogen accumulation capacity of Nephrolepis, demonstrating its potential as an effective biological tool for nutrient management. The notably lower soil nitrate levels observed in the enhanced treatment indicate that Nephrolepis serves as an effective biological agent for reducing nutrient loss through leaching. This finding has important implications for sustainable oil palm agriculture, as it demonstrates how the integration of this plant species can enhance the environmental sustainability of palm oil cultivation systems. The capacity of Nephrolepis to regulate soil nitrate concentrations suggests its potential value as a natural solution for improving nutrient management in agricultural landscapes. The results of this study show promising potential for application among oil palm farmers in various regions; however, its implementation requires comprehensive consideration of several factors. The adaptability of Nephrolepis to different climatic conditions and soil characteristics is a key consideration, as each region has its own unique environmental conditions. Differences in plantation management practices and fertilization patterns applied across regions may also affect the effectiveness of Nephrolepis in mitigating nitrate leaching. Additionally, the socio-economic capacity of farmers in the target regions to adopt and manage Nephrolepis as a cover crop needs to be carefully evaluated. To ensure successful implementation, adaptation and validation research in the target regions is needed to confirm effectiveness and optimize the application of this technique in line with local conditions. Extension and training programs for farmers are also critical components to ensure the successful adoption of this system in new areas. Life cycle assessment results further validated the environmental benefits of this approach, showing reduced impacts across multiple categories including greenhouse gas emissions, eutrophication, and water consumption. The observed soil chemical property improvements and stable soil moisture-temperature relationships indicate that Nephrolepis integration can contribute to overall soil health maintenance. These findings provide strong evidence that incorporating Nephrolepis under enhanced management practices offers a sustainable solution for nutrient management in smallholder oil palm ecosystems, potentially reducing environmental impacts while maintaining agricultural productivity. Future research should focus on long-term monitoring and optimization of management practices to maximize these benefits across different agricultural contexts.

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