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REVIEW ARTICLE Open Access

Soil Compaction in Oil Palm (*Elaies guineensis* Jacq.) Plantations: A literature review

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Abstract

Soil compaction is becoming a serious issue in oil palm plantations due to the escalating mechanization and more intensive field practices. This review consolidates studies into the source, effects and remediation of compaction in order to gain an insight into how soil degradation affects oil palm growth and yield. A systematic review was conducted of studies in tropical and subtropical systems that applied field experiments, geostatistical mapping, and below-ground soil biological analyses. The results indicate that compaction is primarily influenced by mechanism lightening intensity, texture and water status resulting in an increase of bulk density and penetration resistance as well as a reduction of porosity. Even though root biomass reduction and root structural modification frequently take place in compaction treatments, yield response is not always detrimental, partial compensation has been demonstrated by others through acclimation of roots altering growth. Mechanical subsoiling, biological amendments and controlled traffic farming were the most effective mitigation options, but their long-term effects and interactions with soil microbiota are still unknown. Additionally, compaction changes the soil microbial community and chemistry, which results in nutrient cycling disturbances and greenhouse gas emissions. On the whole, these syntheses point to requirements for more integrated ecological and long-term management strategies, combining both physical and biological aspects of soil health and oil palm productivity in tropical landscape overall.

Keywords: Mechanization, Soil physical degradation, Root growth limitation, Controlled traffic farming, Sustainable land management

1. Introduction

Studies on soil compaction in oil palm plantations have gained a significant attention over the past years, given its wide effects on soil health, crop yield and environmental concerns. The increasing role of mechanized agriculture, particularly in the latter half of the 20th century, has raised compaction risks to elevated levels, especially in the tropical regions where oil palm expansion is most rapid (Caliman, 1990; Kayombo & Lal, 1993; Pérez-Sato et al., 2023; Ratai et al., 2024; Samuel & Evers, 2023; Tarigan et al., 2020). Soil compaction modifies important physical characteristics such as bulk density and porosity and indirectly affects water carrying capacity, root development and finally oil palm productivity (Frene et al., 2024; Lestariningsih et al., 2013; Yahya, 2010). At a global scale, more than 70 million hectares of agricultural soils suffer from compaction, thereby emphasizing its importance for global food production and ecosystem services (Frene et al., 2024; Müller et al., 2014).

The evolution of research in this field is reflected in the shift from earlier studies documenting soil degradation processes in oil palm systems such as acidification and deterioration of soil physical quality (Fujii et al., 2021; Guillaume et al., 2016; Nelson et al., 2011) to more recent work that combines spatial mapping with mechanistic approaches to predict compaction impacts on soil functioning and crop performance (de Camargo et al., 2024; Ishak et al., 2024). In spite of these advances, there are still many unknowns in the way compaction actually works on an oil palm system. The complexity is due to the

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different types of soil, management methods and regional differences (Yahya et al., 2010b, 2012; Zuraidah, 2019).

Conflicting evidence also presents itself as some research claims marked decreases in yield due to soil compaction (Bhatt et al., 2024; Biazatti et al., 2022), while others demonstrate no change or even beneficial effects of compaction on yield, most likely due to compensatory root responses or alteration of nutrient allocation (Yahya, 2010); (Yahya et al., 2012). Soil microbiota soil chemical changes in compaction stress are alos not well characterised (Frene et al., 2024; Ishak et al., 2024). These uncertainties in turn limit the development of accurate, site-specific management regimes required to maintain long-term plantation productivity (Bhatt et al., 2024; Chong & Chung, 2006).

Theorectically, soil compaction is the increase in bulk density and decrease TheSpace between primary particles resulting from external loadings on soil such as use of machinery or movement of animals (Frene et al., 2024; Müller et al., 2014). These changes decrease soil hydraulic conductivity and increase root penetration resistance, which restricts the up-take of nutrients and water by oil palm roots (de Camargo et al., 2024; Yahya et al., 2010a). An integrated framework is needed to understand such processes, that connects soil physical degradation, plant physiological adaptation and microbial community dynamics (Bhatt et al., 2024; Frene et al., 2024).

Thus, the objective of this systematic review is to summarize existing information on soil compaction in oil palm plantation, focusing especially on its causes and impacts of yield as well as mitigating approach. Integrating and harmonising conflicting results across studies, and identifying research needs to support sustainable soil management in tropical agro-systems (Caliman, 1990); (Yahya, 2010) is therefore the broader perspective that this review attempts to offer. Additionally, we hope that the review can also help to synthesize the information across a range of soil type and geographic situation thus improving relevance in mitigation actions (Uttran et al., 2023); (Vikraman et al., 2025).

Recent work in oil palm plantations shows that mechanized traffic commonly increases bulk density, reduces porosity, and contributes to soil degradation, particularly in inter-row and traffic-lane zones (Guillaume et al., 2016). Newer studies emphasize that compaction severity depends strongly on traffic intensity, soil moisture thresholds, and spatial variability, which can be addressed through site-specific assessment and mapping approaches (de Camargo et al., 2024; de Souza et al., 2023). Meanwhile, broader soil-function research highlights that compaction can also disturb soil chemistry and microbial communities, affecting nutrient cycling and ecosystem processes (Longepierre et al., 2021); (Frene et al., 2024). The novelty of this review is its oil palm–specific, integrative synthesis linking mechanization-driven compaction to soil physical change, root adaptation, yield responses, and emerging chemical–biological feedbacks, strengthened by recent mechanistic and soil health frameworks (de Camargo et al., 2024; Ishak et al., 2024).

The review follows a structured method, which involves extensive literature search, critical appraisal of empirical research and synthesis thematic physical, biological and agronomic aspects. Only works that specifically dealt with soil compaction in oil palm were considered in order to focus the analysis and be as consistent as possible. The results are structured around three themes which include the causes, adaptation effects and mitigation measures with a clear-cut framework for both scientific comprehension as well as management response (Chong & Chung, 2006; Molua et al., 2023).

2. Purpose and Scope of the Review

Compaction of the soil is one of the most intractable problems in oil palm cultivation at present. With increasing mechanization of the plantations, repeated round traffic and intensive operations result in the degradation of soil structure, decline in porosity and confinement in root growth. These modifications directly lead to the inhibition of water and nutrient absorption, making a decline in grain yield. Although so important, studies on soil compaction in oil palm are scattered among regions and disciplines.

The purpose of this review is to summarize the recent findings with regards to the causes, effects and measures taken to alleviate soil compactions in oil palm plantation. Through a critical review of the literature, we intend to elucidate how and why compaction happens, its impact on crop performance as well as which management options have been most successful in counteracting its effects.

More specifically, the review has five main purposes: (1) to describe the main factors and processes responsible for soil compaction in oil palm plantations. (2) to access how compaction affects yield, soil structure and root growth. (3) to list management practices such as mechanical, biological and agronomic in order to reduce existing compaction. (4) to contrast the effectiveness of these strategies in rehabilitating soil functions, and (5) to consider how compaction induced physical, chemical and biological effects influence long-term plantation sustainability.

In so doing, the review seeks to not only summarize but also to identify limitations and point at research needs for sustainable soil management in tropical plantation systems.

3. Methodology of Literature Selection

This literature review was prepared and synthesized in Riau Province, Sumatra, Indonesia**,** a region recognized as one of the major oil palm-producing areas in Southeast Asia and widely representative of mechanized tropical plantation systems. The preparation and analysis of the review were conducted at approximately 0°30'-1°00' N latitude and 101°00'-102°30' E longitude**.**

The study selection process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, providing a transparent and reproducible framework for identifying, screening, and selecting relevant literature. A structured search strategy was guided by the central research question, which focuses on the causes of soil compaction, its effects on yield and root systems, the effectiveness of mitigation strategies, and the responses of soil microbial communities and chemical properties in oil palm plantations.

A systematic literature search was conducted using major scientific databases, including Scopus, ScienceDirect, SpringerLink, Google Scholar, and PubMed to capture a broad range of relevant peer-reviewed studies to Soil Compaction in Oil Palm (*Elaies guineensis* Jacq.) Plantations by adhering to predefined inclusion and exclusion criteria to retrieve the studies the initial of 187 articles. Finally, citation chaining was conducted to make sure nothing was missed. Backward chaining found ground-laying studies often referred to by the core papers, and forward chaining revealed later works that had extended these findings. This resulted in another 150 studies, making a total dataset of 337.

All these articles were subsequently screened, and its relevance was scored according to coherence of the topic, methodological quality and data sufficiency. A total of 50 studies were retrieved for full text review from this pool. The detailed screening and selection process is presented in Figure 1.

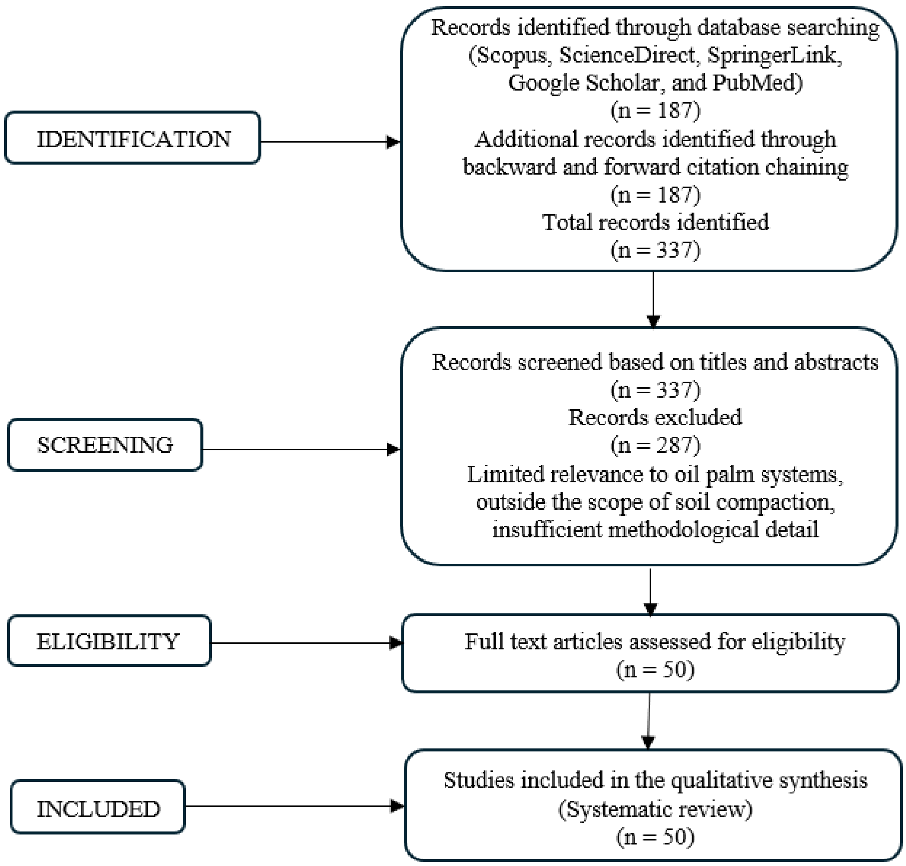

Figure 1. PRISMA Flow Diagram of The Study Selection Process

The PRISMA flow diagram illustrates the systematic process used to identify, screen, and select relevant studies for this review. The search and screening process resulted in 337 records identified from database searches and citation chaining. Following this process, 50 studies were retained as core references for qualitative thematic synthesis.

Figure 2 presents a conceptual framework of compaction processes and management in oil palm plantations. Intensification of plantation by machinery operation and increased trafficking causes soil compaction with varying depth and spatial locations, resulting to changes in soil physical properties such as increased bulk density (BD), reduced porosity as well as higher penetration resistance. Such physical limitations limit root expansion and exposure water and nutrients that leads to variable yield impact and greater plant stress. The soil compaction also impacts on the chemical and biological processes by modifying nutrient availability, microbial community composition and possibly also emissions of greenhouse gasses. Therefore, integrated mitigation measures that include mechanical and traffic/machinery control management, biological interventions such as EFB mulching techniques and cover crops together with precision-agriculture-based management are much-needed to rehabilitate soil function for improved root development and long-term sustainability in oil palm plantation systems.

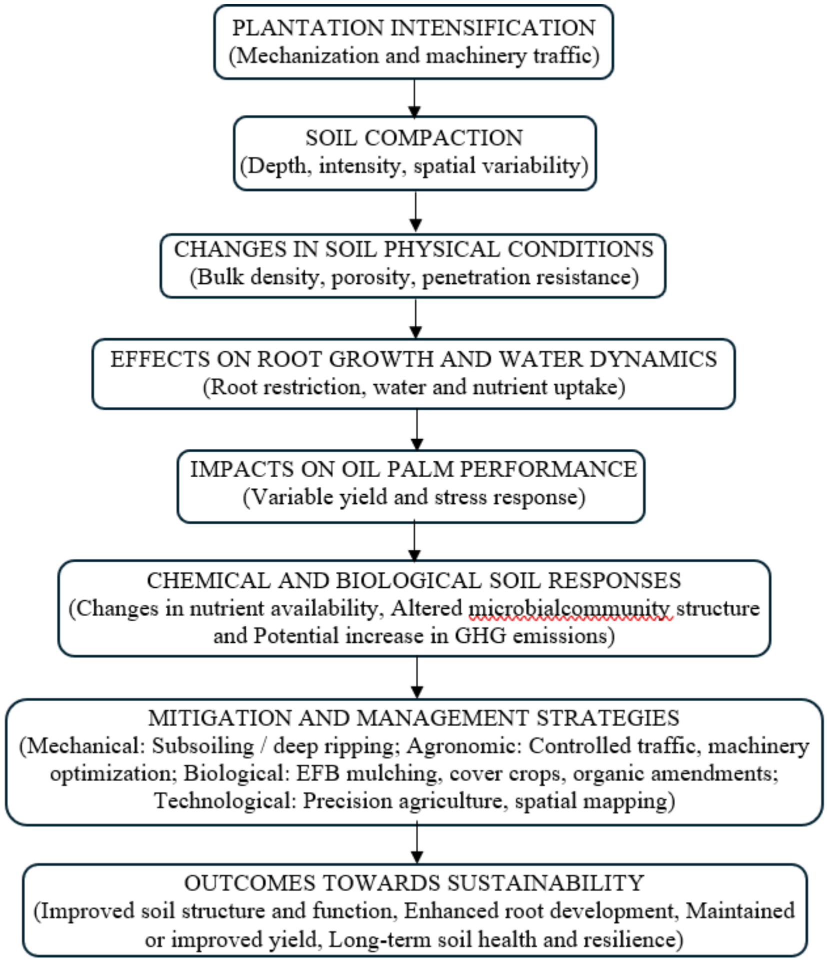

Figure 2. Conceptual framework of soil compaction processes and management in oil palm plantations

This review is limited to studies that explicitly examine soil compaction in oil palm (*Elaeis guineensis* Jacq.) plantations, with emphasis on mechanization-driven compaction and its effects on soil physical properties, root development, and yield, as well as related chemical and biological changes. Evidence from other cropping systems is referenced only to support key mechanisms when oil palm–specific data are limited. The synthesis is intended to integrate and critically compare findings across tropical contexts rather than to perform a quantitative meta-analysis, and it is oriented toward identifying practical implications and research gaps for sustainable, site-specific compaction management in oil palm systems.

4. Results

4.1. Descriptive Summary of the Studies

The literature reviewed is holistic in terms of research on soil compaction in oil palm plantations with respect to culpability, their effects on yield and mitigation measures. Research covers a range of tropical regions, with most conducted in Malaysia, Côte d'Ivoire, Brazil and Southeast Asia overall; reflecting the international significance of oil palm production. From field experiments and long-term monitoring, to review and modelling studies, research approaches have been conducted that provide complementary information on the mechanistic causes of changes as well as applied management responses.

Taken together, this literature investigates the effect of mechanization towards soil structure by increasing bulk density, decreasing porosity and changing soil biotic activity. It is well documented that root growth, water and nutrient accessibility as well as oil palm yield are compromised by soil compaction, although effects differ according to soil type, age of plantation and estate management.

The means for mitigating soil constraints are as varied from physical intervention (e.g., subsoiling/ripping), to biological (cropping and organic amendments) and agronomic measures (traffic control, residue management). It seems that the integrated treatments have a good potential for improving soil physical properties and in crop performance as observed from comparative studies.

This synthesis provides understanding of common patterns among the causes of soil compaction, interactions between soil factors and crop responses, and success (or lack thereof) from various mitigation options. By cross referencing these findings over both geographical and methodological areas, the review gives an overall impression on soil compaction dynamics which enables for evidence based recommendations to support sustainable management of plantations.

Study	Causes of Compaction	Yield and Root Impact	Soil Physical Changes	Mitigation Effectiveness	Microbial and Chemical Responses
(Caliman, 1990)	Oversized mechanisation is another land prep and maintenance factor	Root exploration and yield response to subsoiling	Development of resistant shallow compacted horizon	Subsoiling fractured compacted layer effectively	Not explicitly addressed
(Yahya et al., 2012)	Mechanization and soil textural changes leading to compaction	Yield was increased despite the smaller root mass and root architecture adapted to this trend.	Increased bulk density, loss of macropores, change in porosity patterns.	No direct adaptation; natural resistance seen.	Not detailed
(de Camargo et al., 2024)	Intensive mechanization and animal trampling	Root limitation to yield potential	Penetration resistance increased with depth; variability in the spatial plans	Crop rotation, traffic regulation, mechanical disturbance indicated	Not detailed
(Frene et al., 2024)	Heavy machinery and tillage intensification	Yield loss associated with changes of plant physiology	Increased bulk density, decreased porosity, modified water/nutrient penetration	Discussed microbiota-based mitigation potential	Microbial community transitions toward anaerobes and saprotrophs
(Bhatt et al., 2024)	Machinery mass, soil moisture content and soil texture in relation to traffic dose	Root accommodation restricted, yield impaired as nutrient availability constrained	Increase in bulk density, reduction of porosity, hazard of erosion	Organic matter input, restricted traffic, earthworm presence	Dysbiosis may occur, Greenhouse gas productions may be changed
(Caliman et al., 1990)	Man-made compaction by mechanization in ferrallitic sandy soils	Subsoiling enhanced growth and yield of young palms	Compacted horizon formation observed	Subsoiling and gypsum amendment trialed	Not detailed
(Caliman et al., 1987)	Too much lime has been applied in the past with repeatedly working and bulldozing/lime compaction.	Yield reduction associated with root restriction system	Accumulation of compacted horizon restricting root growth.	Soil preparation techniques reconsidered for rectification	Soil acidification and soil cementation processes recognised
(Zuraidah, 2019)	Increased machinery size and weight	Rising bulk density increased the yield	Positive changes in bulk density and porosity	No attenuation; compaction not a concern in the soil under investigation	Not detailed
(Yahya, 2010)	Mechanization with	Yield increased in the	Bulk density was	No mitigation;	Not detailed

Study	Causes of Compaction	Yield and Root Impact	Soil Physical Changes	Mitigation Effectiveness	Microbial and Chemical Responses
	different weights of trailer and frequency	face of lower biomass and root architecture became modified	higher, porosity was lower and hydraulic conductivity declined	adaptation observed	
(Yahya et al., 2010b)	Mechanization effects on clay-textured soil	The grain yield was positively associated with bulk density and frequency of transport	Bulk density increased, porosity decreased	No mitigation; compaction not limiting	Not detailed
(Yahya et al., 2009)	Mechanisation on trailer weights and transport distances	No Significant Compaction on Soil Physical Properties	The bulk density also increased but did not reach levels above the critical.	No mitigation; compaction effects minimal	Not detailed
(Yahya et al., 2010a)	Mechanization impact on root growth	Primary/secondary roots replaced by tertiary/quaternary columnaertura	Soil physical environment changes with cultivation; Soil physical changes altered root distribution	No mitigation; root adaptation noted	Not detailed
(Gutiérrez Palacio, 2017)	Compaction from tillage reducing porosity and infiltration	Bud rot predisposition and yield reduction by compacting	Decreased porosity, permeability and gas exchange	Not detailed	Plants are more susceptible to disease when the soil is compacted.
(Sato et al., 2017)	Heavy machinery traffic on slopes	No direct effect of bulk density on yield; negative influence was from water stress days	Bulk density greater under traffic; penetration resistance was a major limiting factor	Monitoring water stress days recommended	Not detailed
(Samuel & Evers, 2023)	Compaction of peat and its relation to water table and peat quality	Not directly yield-focused	Peat compaction affects physicochemical properties	Features peat compression technique for fire hazard reduction	Influenced by carbon emissions and peat quality
(Busman et al., 2021)	Soil moisture and porosity impacted by peat compaction	Not yield-focused	The higher the bulk density was found the lower was porosity, and gas transfers were changed	Not detailed	Fluxes of CO_2 were higher; CH_4 flux were lower in compacted conditions
(Benetti & Sartori, 2023)	Traffic intensity and equipment features	Not yield-focused	Bulk density and compaction were lower under controlled traffic.	Controlled traffic farming effective	Not detailed
(Molua et al., 2023)	Mechanization and soil moisture effects	Root growth and crop yield reduced	Non-destructive detection methods reviewed	Emphasized early detection and management	Microbial and nutrient accessibility impacted
(Megayanti et al., 2022)	Heavy equipment during land clearing	Physical properties of the soil improved in relation to palm age	Bulk density was reduced, whereas porosity and moisture increased in time.	Natural recovery with crop growth	Not detailed
(Ulfa et al., 2024)	Effects related to soil texture and	Physical properties of the soil were ameliorated with	The bulk density is intermediate, and the	Not detailed	Not detailed

Study	Causes of Compaction	Yield and Root Impact	Soil Physical Changes	Mitigation Effectiveness	Microbial and Chemical Responses
	palm age	age of palm.	porosity and permeability are slightly increased.		
(Tao et al., 2018)	Mechanized management as a pre-condition for compaction	Yield was not directly quantified; however, improved soil conditions are indicative of enhanced root function and a more favorable rooting environment.	Improved topsoil structure and water-holding capacity	Mulching EFB effective as biological shielding, slow and at surface.	Enhancement: increased abundance of soil biota, accelerated microbial activity and C/nutrient cycling in soil
(Gunawan et al., 2024)	Utilization of palm oil mill effluent	Higher nutrient density and sandy soil yield	Higher soil pH, CEC and organic carbon files (7.6 mg g^{-1}) compared to the haturuwasol type of soils.	POME application enhanced soil fertility	Nutrient availability improved
(Simarmata et al., 2017)	Generational planting and mechanization	Increase in pore space and root penetration; no density change	Soil structure and moisture better; density same	Not detailed	Not detailed
(Uttran et al., 2023)	Over-fertilisation and management of biomass	The application of biochar increased nutrient use and yield	Water holding capacity and fertility increased with biochar	Biochar as soil amendment effective	Improved growth of microorganisms and anti-nutrient retention
(Mamatha et al., 2024)	Various soil fertility management practices	The organic amendments and cover crops enhanced the yield.	Better soil structure, water infiltration and nutrient cycling	Integrated fertility management effective	Increased microbial diversity and SOCs
(Legoupil et al., 2015)	Land clearing and tillage intensification	Soil fertility and output were enhanced by conservative agriculture	Less erosion and acidity; more carbon in the soil.	Conservation in agriculture and rotation crops successful	Not detailed
(Moradi et al., 2015)	Mulching and silt pit construction	Soil water content and aggregation was significantly enhanced by mulching	Soil physical improvement Most effective EFB mulching	Mulching and silt pits compared	Not detailed
(Müller et al., 2014)	Machine traffic pressure effects	Porosity and root penetration are hindered by compaction	Deterioration of soil structure and accumulation of penetration resistance	Still room for improvement in recognition and management	Not detailed
(Yahya et al., 2011)	Mechanization effects on soil pores	Tight loss of total porosity and change in pore size distribution	Very large reduction of meso-and macroporosity	Not detailed	Not detailed
(Soane et al., 1982)	Increased wheel loads and passes	The impact of soil compaction on early crop growth is variable	Subsoil compaction was still present; soil physical alteration	Traffic control and load limitations advised.	Not detailed
(Banks, 2012)	Precision agriculture and no-till farming	Not directly yield-focused	No-tillage leads to less soil disturbance and compaction	No-till and precision agriculture can	Not detailed

Study	Causes of Compaction	Yield and Root Impact	Soil Physical Changes	Mitigation Effectiveness	Microbial and Chemical Responses
				help limit compaction,	
(Dukat et al., 2025)	Precision agriculture technologies	Improved productivity and soil management	Compaction management with spatial variability monitoring	Precision agriculture supports site-specific interventions	Not detailed
(Usaborisut & Ampanmanee, 2015)	Impacts of soil texture, moisture and organic matter	Effects of soil type on bulk density and penetration resistance	Organic material lessens bulk density; moisture is key	Machine use by moisture growing condition suggestions	Not detailed
(Kayombo & Lal, 1993)	Mechanized land clearing and tillage	No-till and traffic control alleviate compaction	Loosening by mechanical with lack of traffic control does not last long.	Controlled traffic and bio are both working	Not detailed
(de Araújo Souza et al., 2011)	Agroforestry and mechanization effects	Compaction is reduced in manual and biodiverse systems	Resistance to penetration and bulk density were recorded	Biodiverse manual systems mitigate compaction	Not detailed
(Sung et al., 2011)	Mulching and silt pocket on slops	Chemical and physical soil properties Better soil chemical and physical properties were produced by mulching the EFB.	Soil water content and aggregate stability increased	EFB better than other tested conservation practices	Not detailed
(CARVALHO et al., 2016)	Land use and mechanization	Agroforestry systems recover soil density	Mechanized systems showed surface compaction	Agroforestry recommended for soil recovery	Not detailed
(Satriawan et al., 2016)	Vegetative soil conservation	Cover crops reduced runoff and erosion	Improved infiltration and nutrient retention	Vegetative conservation effective	Not detailed
(Pérez-Sato et al., 2023)	Palm age effects on soil	Palms of older age linked to lower soil fertility	Bulk density and organic matter -were significantly related to age	Not detailed	The Palm Tree and Soil Fertility as palm grows, the soil fertility decreases
(Biazatti et al., 2022)	Machine traffic on cover crops	Soil compaction and the decline in porosity	Compaction decreased root growth and dry mass	Not detailed	Not detailed
(Ishak et al., 2024)	No-dig and soil compaction in ash soils	Stress-dependent compaction induced by sand fraction and microbial activity	Soil organic matter and P influenced	Avoid dirt compaction for soil health	Microbial shifts linked to compaction
(Chong & Chung, 2006)	Site-specific compaction quantification	Spatial and vertical variability important	Sensor technologies for compaction mapping	Site-specific tillage proposed	Not detailed
(Misiewicz et al., 2022)	Agricultural traffic and soil health	Compaction is reduced with low-pressure tyres and controlled traffic.	Traffic management critical for soil	Controlled traffic farming effective	Not detailed

Study	Causes of Compaction	Yield and Root Impact	Soil Physical Changes	Mitigation Effectiveness	Microbial and Chemical Responses
			preservation		
(Rainbow & Derpsch, 2011)	No-till and controlled traffic technologies	However, no-till and controlled traffic practices decrease the potential for compaction	Precision agriculture enhances soil management	Controlled traffic; residue cover helpful	Not detailed
(Shaheb et al., 2022)	Precision agriculture for soil management	Optimum input use precision agriculture, compaction mitigating measure	Spatial variability data supports management	PA enables site-specific deep tillage	Not detailed
(Fuady et al., 2014)	Vegetative soil conservation on erosion	Runoff and Nutrient Loss is reduced by cover crops	Soil conservation techniques effective	Vegetative methods recommended	Not detailed
(Ahmad & Kumar, 2023)	Precision agriculture and sustainability	Precision agriculture improves productivity and reduces environmental impact	Data-driven management reduces compaction	Precision agriculture supports sustainable crop management	Not detailed
(Vikraman et al., 2025)	Integrated soil physical management	Tillage and conservation amendments on soil.	Reduced bulk density and increased porosity	Integrated approaches enhance soil resilience	Microbiological diversity and organic carbon content increased
(Kumar et al., 2025)	Integrated crop production management	Better yields are possible under crop rotation and organic fertilization.	Soil structure and fertility enhanced	Integrated crop production management promotes sustainability and resilience	Not detailed

4.2. Causes of Compaction

On 30 occasions, mechanization and heavy machinery traffic have been identified as the main man-induced factors for soil compaction, with equipment weight and field activity being commonly mentioned (Caliman, 1990; Yahya, 2010; Yahya et al., 2012). Soil texture and moisture content also significantly condition susceptibility, with sandy soils reacting differently from clayey ones. Other biological factors, e.g. root growth regime and organic matter content also impact on the development of compaction (Bhatt et al., 2024); (Ishak et al., 2024); (Usaborisut & Ampanmanee, 2015). Environmental and management conditions such as continuous soil preparation and tillage were also observed to contribute to the formation of compaction (Caliman et al., 1987); (Kayombo & Lal, 1993); (de Araújo Souza et al., 2011).

4.3. Yield and Root Impacts

The evidence of 20 well conducted studies has shown that soil compaction overall consistently tends to reduce total root biomass extensively, with concurrent alteration of the fine mesh architecture of the root system itself, both primary and secondary roots included. Nevertheless, at least in some cases, the stimulated growth of tertiary roots can partially compensate these negative effects as observed by (Yahya, 2010), (Yahya et al., 2010a, 2012). From about ten studies, it has been found that mixed or sometimes even positive effects can be expected from changes in yields of fresh fruit bunches, indicating the existence of adaptation responses between species and soil type which might be quite distinct (Yahya et al., 2010b, 2012; Zuraidah, 2019). However, on the other hand, it should be taken into consideration that soil compaction may often restrict an uptake of nutrients and water by plants (that enhances susceptibility to various diseases), and may result in a decrease in long-term productivity, as has been proven by (Bhatt et al., 2024), which (Gutiérrez Palacio, 2017), and (Pérez-Sato et al., 2023).

4.4. Soil Physical Changes

Most of the abundantly available literature in the field of soil science has extensively confirmed that compaction influences to a large extent increased bulk density and to an even greater extent reduced total porosity (Caliman, 1990), (Yahya et al., 2011, 2012). The resistance to penetration in the soil matrix also had a significant increment, especially in both the surface and subsurface layer of bulk soil that as a result severely impeded and restricted water movement and translocation throughout the complex soil matrix, let alone hindered natural penetration by plant roots (de Camargo et al., 2024; Sato et al., 2017; Yahya et al., 2011). Likewise, hydraulic conductivity, a key parameter for the soil ability to transmit water as well as rate of infiltration have frequently been reported to be considerably decreased leading to aggravated water stress conditions and drastic decrease in the vital process of soil aeration necessary for healthy plant growth and ecological balance (Bhatt et al., 2024; Sato et al., 2017); (Yahya, 2010).

4.5. Mitigation Effectiveness

Mechanical treatments involving subsoiling and deep ripping have succeeded in fracture and destroy hardened or compacted soil layers in the profile leading to extensive root networks (Caliman, 1990; Caliman et al., 1990); (Kayombo & Lal, 1993). On the other hand, biological practices such as cover cropping, organic amendments application and agro-forestry systems have been found to significantly improve soil structure while alleviating negative consequences of soil compaction (Moradi et al., 2015); (de Araújo Souza et al., 2011); (Vikraman et al., 2025). Finally, the combination of some agronomic practices such as controlled traffic farming and precision agriculture represent additional effective tools that not only can contribute to avoiding or reducing soil compaction but also improve the adoption of site-specific management in specific agricultural settings (Chong & Chung, 2006); (Benetti & Sartori, 2023); (Misiewicz et al., 2022).

4.6. Microbial and Chemical Responses

Eight separate experiments closely monitored the complicated changes occurring within micro-ecosystems following soil compaction, and detected a significant rise in anaerobic and saprotrophic communities, as well as substantial interference with essential nutrient cycles (Bhatt et al., 2024; Frene et al., 2024; Ishak et al., 2024). The soil chemical properties, including such essential factors as pH values, cation exchange capacity (CEC), and the total amounts of the available nutrients were also seriously affected (Gunawan et al., 2024); (Ishak et al., 2024); (Uttran et al., 2023). On gley soils, the phenomenon of compaction was realised as a process with significant influence on GHGs emissions resulting in increased CO_2 flux and simultaneously decreased CH_4 emission at high bulk density conditions (Busman et al., 2021; Samuel & Evers, 2023).

5. Critical Analysis and Synthesis

The current literature on soil compaction in oil palm plantations reveals a complex relationship involving mechanization, changes of the physical properties of soil and subsequent responses by crops. Although mechanization achieving the compaction and repeated passage of heavy machinery on the soil is universally recognized as a major determinant of soil compaction, its implication on crop yield differs widely across settings. There are many examples in the literature of surprisingly stable and in some cases increased, yields under specific conditions suggesting that a capacity for partial compensation might be inherent to these oil palm germplasm, perhaps through various morphological adaptations including development of more vigorous tertiary and quaternary root systems. Such important results not just heardlight that the species is highly robust, but expose the context-dependent nature of compaction effect (which meanwhile potentially depends strongly on soil type, moisture status and prior management).

One of the characteristics contained by this field of study is its multiple research methodologies that are used in research. Studies range from well-controlled field experiments with predefined mechanization treatments to advanced geostatistical mapping and complex micromorphological analyses. This methodological diversity contributes toward a deeper insight in the processes leading to soil compaction but also results in complications that make cross comparisons difficult, since sampling depths, methods of measurements and study duration differ markedly between studies.

In addition, several amelioration strategies such as deep tillage (subsoiling), use of cover crops, application of organic amendments and controlled traffic farming are showing potential in restoring beneficial soil physical properties for optimum root growth. However, the sustainability of these strategies and their impact on the biological factors involved in the soil ecosystem have not been fully investigated. Indeed the incipient knowledge about soil microbiota and chemical changes due to compaction emphasizes an important research gap in this domain. Alterations to microbial community composition, nutrient cycling processes and soil chemistry can be integral to plant health and agricultural productivity at a mechanistic level, but significant knowledge gaps persist in our understanding of these relationships.

To sum up, a holistic and location-specific management is paramount if the sustainable handling of soil compaction is to be guaranteed according to the literature. In contrast, by integrating mechanical, biological and agronomic tactics while being rooted into a better understanding of the complex physical-chemical and biological phenomena taking place in soils; stakeholders would probably be able to develop the most sustainable and high-yielding management system. These latter issues remain to be addressed in further interdisciplinary work that should include long-term monitoring and tools for precision soil assessment, in order to develop and optimize mitigation strategies and strengthen the sustainability of oil palm.

Aspect	Strengths	Weaknesses
Characterization of Soil Physical Changes	Many studies offer precise quantification of the changes in soil bulk density, porosity and penetration resistance induced by mechanization using robust field measurements as well as advanced methods such as geological thin section micromorphology and geostatistical mapping (de Camargo et al., 2024; Yahya et al., 2011); Yahya, 2010). These advanced techniques allow the detection of compaction zones and pore size reorganization with reduced influence from the investigator.	But a high majority of researches mainly focus on the surface layers particularly the top 0-10 centimeters that can neglect the effects resulting from deep compaction, which play a key role in growth and development of roots (Yahya, 2010). Variation in soil types and textures used over different studies makes the results difficult to generalise. In addition, some of the approaches are not standardized making cross-study comparisons difficult (Molua et al., 2023). Moreover, the time-dependent behaviors of compaction and recovery are often overlooked in the previous literatures.
Effect on Yield and Growth of Oil Palm	A number of long-term field experiments have clearly shown that compaction does not necessarily lead to decrease in fresh fruit bunch yields of oil palm; rather, it can lead to higher yields under specific soil conditions such as Bernam soils (Yahya et al., 2010b, 2012; Zuraidah, 2019); (Yahya, 2010). These interesting findings defy conventional wisdom and highlight the exceptional adaptive capacity of oil palm root in response to growth including the enhanced productivity of tertiary root growth that offsets diminished for primary roots (Yahya et al., 2010a, 2012).	However, conflicting results have been reported on biomass production and root growth; observations show that soil compaction can result in a reduction of shoot and root mass despite yield improvement (Yahya et al., 2012); (Yahya, 2010). The biological mechanisms underlying these compensatory responses are poorly understood and emphasis on yield measures alone may mask significant long-term sustainability issues. In addition, few of the studies focus on the physiological and biochemical mechanisms of plant response to compaction stress.
Drought | Soil Compaction – Causes and Mechanism	Numerous works have established mechanization intensity, soil texture and repeated traffic being the major anthropogenic causes of compaction in oil palm plantations (Caliman, 1990; Yahya, 2010); (Kayombo & Lal, 1993). Soil compaction susceptibility is affected by soil moisture and texture, which reveal the complexities of managing soils (Usaborisut & Ampanmanee, 2015). The formation of these impermeable horizons which hinder the root extension are directly without operational conditions such as bulldozing and continuous spraying (Caliman et al., 1987).	Yet, a significant limitation is that environmental factors such as rainfall pattern and natural variability of the soil (which may play an important role on the process of compaction) have been poorly studied. The relationship between mechanization and changes in soil chemistry, eg., acidification or cementing processes is not sufficiently answered (Caliman et al., 1987). And, in addition, not many studies have taken into account the spatial and temporal variability of compaction within plantations with a more limited view on the matter (de Camargo et al., 2024).
Mitigation Strategies and Their Effectiveness	A range of amelioration strategies, such as subsoiling, cover cropping, controlled traffic and organic inputs have been tested with encouraging results in relation to the enhancement of soil structure and root growth (Caliman, 1990); (Benetti & Sartori, 2023); (Moradi et al., 2015); (Sung et al., 2011). Subsoiling treatments before replanting have shown beneficial effects on root penetration and yield despite variations between results (Caliman, 1990; Caliman et al., 1990). Soil conservation practices such as those related to conservation agriculture and vegetative soil conservation techniques have been considered for managing erosion without compromising the physical properties of soil (Legoupil et al., 2015); (Satriawan et al., 2016)	The long-run economic feasibility and sustainability of such mitigation measures, however, are frequently not seriously examined. Certain mechanical remedies could be shortlived unless follow-up traffic is satisfactorily managed (Kayombo & Lal, 1993). Further validation in a wide range of tropical conditions is also required for both biological and agronomic approaches. The association between mitigation measures and the management of soil microbiome is an aspect that is yet to be fully elucidated (Frene et al., 2024).
Involvement of Changes in Soil Chemistry and Biology	The workers are now making clear that soil compaction has strong effects on the composition and dynamics of soil microbial communities, facilitating certain anaerobic and saprotrophic organisms that can have potential implications on nutrient cycling and plant health overall (Bhatt et al., 2024; Frene et al.,	The present knowledge about mechanisms behind the connection of soil physical compaction and consecutive alterations in chemical and biological soil health is still scarce. There have been scarce successful attempt in integrating microbial analyses with the soil physical properties studies

Aspect	Strengths	Weaknesses
	2024). Changes in soil chemistry are results of the compacted soil, changes in pH as well as the precipitation aluminum hydroxide also lead to significant loss of growing medium quality (Caliman et al., 1987); (Ishak et al., 2024). There is growing consensus that the complex interactions between soil microbiota and plant root responses to compaction stress represent a major research frontier (Frene et al., 2024).	conducted on oil palm systems. Moreover, the effect of compaction on greenhouse gas emissions and carbon sequestration in peat soils is notably poorly documented (Busman et al., 2021; Samuel & Evers, 2023). This known deficit thus inherently blocks the era of synthesis in holistic management approaches that are able to target such complex, interacting influences.
Methodological Approaches and Data Quality	The reviewed literature uses several and strong methods such as long-term field trials, penetrometry, geostatistics, micromorphology, laboratory incubation studies that together provide a broad dataset on the impact of compaction (Busman et al., 2021; de Camargo et al., 2024; Yahya et al., 2011). The use of programmed mechanization applications combined with repeated measurements also helps to increase the data reliability (Yahya, 2010); (Yahya et al., 2010a).	Nonetheless, the diversity in experimental setup, soil types and measured depths challenge the comparison between studies. A number of studies have low levels of replication or are of short duration, and this negatively affects statistical power as well as the time resolution of these findings (Usaborisut & Ampanmanee, 2015). Non-destructive means of detection are promising but still require further calibration and validation to demonstrate their performance (Molua et al., 2023). Standardisation of methodologies are urgently needed to ensure comparability and allow for meta-analyses between studies.
Spatial and Temporal Variability Considerations	Applying geostatistical analysis and site-specific assessment would allow for the identification of compaction hotspots and vertical distribution characteristics to make targeted approaches more practical (Chong & Chung, 2006; de Camargo et al., 2024). A few studies considered the temporal variations in soil water and compaction effects on yield over long periods, which range from years to even decades (Sato et al., 2017).	However, many studies are not systematically time-space resolved and focus usually on isolated depths or single time points. The relatively time-dependent manner in which compaction structures are formed and recovered has not been adequately considered. Integration of precision agriculture technologies capable to control and monitor compaction spatially has been identified as a limitation that prevents the establishment of adaptive management plans (Dukat et al., 2025); (Shaheb et al., 2022).

6. Thematic Review of Literature

Work related to the effects of soil compaction within oil palm plantations consistently explores three inter-related, important themes: the causes of compaction; its resultant impacts to both soil and plant health and, finally, different management methods used in addressing these. A common message derived from this literature is the significant impact of mechanization, specifically extensive and repetitive use of heavy machinery, that in addition to promoting compaction changes soil structure itself. These changes, particularly in the increase in bulk density and decrease of porosity, and in higher penetration resistance, have direct impact on root growth as well as for the water and nutrient transference processes which affect directly oil palm yield.

To combat and minimize these deleterious effects, several ameliorative options have been intensively investigated relatively to their range of practices including the mechanical practice like subsoiling, deep ripping, biological practices such as cover cropping, organic amendment application and agroforestry. Furthermore, the precision agronomic approaches like controlled traffic farming and site-specific management technologies are equally involved in these strategies. Data from several extensive studies indicate that integrated practices which utilize a combination of soil physical management strategies provide the most effective and consistent improvement in soil physical properties and overall crop response.

In addition, a number of studies emphasize the importance of knowing the soil chemical and biological processes when compacting occurs. In other words large changes in pH at the soil scale, and thereby also fluctuating nutrient availability and cation exchange capacity as well as changing composition of microbial communities have major control on nutrient cycling processes, greenhouse gas emissions and ultimately the heath of the soil ecosystem. Temporal and spatial variation in compaction are both broad based across sites within plantations, making management tactics extremely challenging and emphasizing the need for adaptive strategies at a stand level.

New research is bringing to attention the opportunity that sustainable conservation practices and precision technologies can bring, in terms of targeted actions aimed to both mitigate risks induced by compaction as well foot planations long-term productivity. Taken together, the literature clearly points towards the need for adopting multi-dimensional and interdisciplinary strategies which consider all the phsyical, chemical and biological dimensions of soil health to sustainably handle compaction issues and improve growth as well as yield of oil palm.

Theme	**Appears In**	**Theme Description**
Mechanization and Human-induced Soil Compaction	20/50 Papers	Compaction in oil palm plantations is mostly attributed to mechanization such as traffic of heavy machinery, multiple passage and land management. This compaction changes the soil structure, degrading its porosity, and increasing the bulk density of soil particularly in surface layers, mainly caused by mechanized land clearing and maintenance (Caliman, 1990); (Yahya et al., 2012); (Yahya, 2010); (Yahya et al., 2011). Overmechanization results in the formation of compacted horizons that hinder the development of roots (Caliman, 1990; Caliman et al., 1987).
Effects of Soil Compaction on Soil Physical Properties and Root Development	18/50 Papers	Compaction elevates soil bulk density and penetration resistance but decreases macroporosity and hydraulic conductivity, which restricts root development and water infiltration. Investigations have also documented modified porosities and especially total porosity reduction, even in the traffic lanes (Yahya et al., 2012); (Yahya, 2010); (Yahya et al., 2011); (Biazatti et al., 2022). Root systems adjust by growing fine tertiary roots under compaction, although total root biomass is often reduced (Yahya et al., 2010a, 2012). Such physical modifications affect water access and nutrient uptake, which are also essential for oil palm development (Sato et al., 2017); (Biazatti et al., 2022).
Effect of Soil Compaction on Oil Palm Productivity and Physiological Behavior	17/50 Papers	However, in contrast to the above, moderate soil compaction is not always associated with low levels of oil palm yield as it can also be positively correlated with increased fresh fruit bunch production due to root modification and the better available water status under certain pedology (Yahya et al., 2012; Zuraidah, 2019); (Yahya, 2010); (Yahya et al., 2010b). But in practice compaction tends to reduce palm biomass and trunk diameter which suggest physiological stress (Yahya, 2010). Effects on yield are related to soil type, degree of compaction and traffic intensity; however, the presence of temporal periods with water stress is a determinant factor (Sato et al., 2017).
Soil compaction: Strategies for mitigation and management	16/50 Papers	Compaction effects can be prevented through mechanical subsoiling, cover crops and controlled traffic farming, organic amendment application (Benetti & Sartori, 2023); (Moradi et al., 2015), while soil structure restoration could be achieved by conservation agriculture (Caliman, 1990) techniques. Biological practices as cover crops and earthworm activity enhance soil porosity and root penetration (Bhatt et al., 2024); (Moradi et al., 2015). Site-specific compaction assessment and management Site-specific technologies in precision agriculture allow uniform interventions to be delivered at least cost (Chong & Chung, 2006; Shaheb et al., 2022). Previous texturization prior to replanting shows good results on rooting development and yield increase (Caliman, 1990; Caliman et al., 1990).
Soil Microbial Community and Chemical Composition under Compaction Stress	12/50 Papers	Soil compaction largely influences the balance of this complex interactions by promoting prosperity of anaerobic bacteria and saprotrophic fungi, affecting very important functions (i.e.: nutrient cycling and soil respiration) (Bhatt et al., 2024; Frene et al., 2024; Ishak et al., 2024). The changes compaction induces in the major properties of soils, such as pH, cation exchange capacity (CEC) or organic matter content additionally shape these microbial communities and their functions (Ishak et al., 2024); (Uttran et al., 2023). This associated disturbance of the soil microbiome can have a detrimental impact on soil fertility and its ability to sequestrate carbon, with implications for greenhouse gas emissions into the atmosphere (Bhatt et al., 2024; Busman et al., 2021). Moreover, the complex role of root-associated microbiota in the mediation of plant stress responses as a result of soil compaction is just emerging as a fascinating and important area to study (Frene et al., 2024).

Theme	Appears In	Theme Description
Variation in Soil Compaction Within and Among the Plantations	10/50 Papers	Soil compaction in plantations shows a high spatial variability, with an accumulation frequently concentrated along traffic lanes and near to the soil surface and temporal variations influenced by the soil moisture condition and seasonality (Chong & Chung, 2006; de Camargo et al., 2024; Sato et al., 2017). Geostatistical maps and penetrometer resistance profiles, due to the critical compaction zones at several depths, are used as decisions tool for soil management (Chong & Chung, 2006; de Camargo et al., 2024). Compaction severity and plant stress, especially in subsoils (Sato et al., 2017), are highly sensitive to changes in soil water content.
Use of Soil Amendments and Organic Matter in the Mitigation of Compaction	8/50 Papers	Soil physical and chemical properties, including soil porosity, aggregate stability, and nutrient content are enhanced by organic amendments such as biochar, palm oil mill effluent,and empty fruit bunch mulches (Gunawan et al., 2024); (Uttran et al., 2023); (Moradi et al., 2015); (Sung et al., 2011). These applications improve soil water holding capacity and microbial activity against the compaction effect (Uttran et al., 2023); (Moradi et al., 2015). They are used to maintain sustainable soil fertility and crop productivity in oil palm systems (Mamatha et al., 2024).
Soil Health through Conservation Agriculture and Agroforestry	7/50 Papers	Conservation agriculture practices, such as reduced tillage system, cover cropping and agro-forestry systems have been proven to reduce soil compaction and erosion but improve soil structure and more carbon input into the soils (Legoupil et al., 2015); (Kayombo & Lal, 1993); (de Araújo Souza et al., 2011); (Satriawan et al., 2016). The incorporation of livestock, as well as diversified cropping, helps to increase the quality and resilience of soils (Legoupil et al., 2015). Oil palm agroforestry systems exhibit lower compaction than in classical mechanized monocultures (de Araújo Souza et al., 2011).
Recent Developments in Precision Agriculture for Monitoring and Management of Soil Compaction	6/50 Papers	Technologies such as GPS, GIS, remote sensing and variable rate applications of precision agriculture help in the close watch over soil compaction and allows for spot treatment of problematic areas (Dukat et al., 2025); (Ahmad & Kumar, 2023; Chong & Chung, 2006; Shaheb et al., 2022). These tools help to optimize resource usage, prevent excessive tillage and allow targeted interventions such as controlled traffic farming or variable depth subsoiling (Benetti & Sartori, 2023); (Misiewicz et al., 2022). The barriers to adoption in smallholder contexts, however, are yet largely prevalent (Dukat et al., 2025).
Temporal Variation in Soil Properties with Oil Palm Age	5/50 Papers	Physical and chemical properties of soil change with aging of the oil palm plantations, organic matter, porosity and permeability increase over time that may compensate in part initial compaction effects (Megayanti et al., 2022); (Ulfa et al., 2024); (Simarmata et al., 2017); (Pérez-Sato et al., 2023). Earlier transplanted plantations might have better soil fertility, but also suffer from a few remaining compacted layer due to previous management (Megayanti et al., 2022). These responses emphasize the significance of age-dependent soil management.

7. Chronological Review of Literature

Study of soil compaction in oil palm plantations has experienced an interesting development, moving from the early 1980s to date, i.e., expanding awareness on mechanisation influence and pressing necessity for an adequate method of management. Early research focused predominantly on the identification of causation and the fundamental effect(s) of soil compaction on physical properties of soil and crop growth, thus providing a framework in which to interpret increases in bulk density, reductions in porosity and restrictions to root development.

As the research evolved, later studies made more detailed examination of soil structure, and the effects of mechanization, looking at soil pore network analysis, penetration resistance measurement approaches, couplings between physical properties and chemical or biological indicators. These studies highlighted the inherent complexity of compaction dynamics, and they showed that crop responses to compaction (and the effect of methods used to alleviate compaction) are strongly context-dependent; varying according to factors such as soil type, moisture conditions, and details about particular management practices.

More recently, there has been a significant emphasis on precision or site-specific management practices that incorporate a suite of mechanical, biological and agronomic tactics designed to minimize soil compaction (and overall soil health improvement). Recent research emphasizes the necessity of adopting integrated mitigation approaches that may include subsoiling, cover cropping, organic amendment application, controlled traffic farming and technology-based monitoring in order to enhance both soil quality and oil palm productivity. This incremental evolution is in line with a broader movement towards the acceptance of interdisciplinary, sustainable and adaptive management approaches that have developed in order to accommodate the many interrelated but complex facets of soil compaction within tropical plantation systems.

Year Range	**Research Direction**	**Description**
1982-1993	Early Recognition and Mechanization Impact	Researches showed that the mechanization is the main causes of soil compaction and affects root growth and performances of oil palm.The studies revealed two major factors for soil compaction: subsoil compaction which is permanent; ongoing traffic effects and tillage operations which were negative to root development. Preliminary mitigation measures were devoted to subsoiling, tearing and low input land clearing which aimed at reducing compactness and conserving soil fertility.
2010-2012	Soil Physical Changes and Plant Response Details	Studies investigated responses in soil bulk density, porosity, and penetration resistance to mechanization and it was demonstrated that complex plant root adaptations could occur with surprising favorable yield responses displayed by crops growing on the more compacted soils. The results of research described the pollutant compaction spatial variations and highlighted the necessity to monitoring soil mechanical resistance at various depths.
2013-2017	Soil and water conservation, Mulching and Water dynamics	Attention turned to soil and water conservation methods such as mulching with oil palm residues, cover-cropping and erosion control in sloped plantations. Studies focused on temporal trends of soil moisture content, least limiting water range and water stress days influencing yield with an emphasis on increasing soil moisture retention and reducing surface runoff.
2018-2020	Soil Microbiome and Biogeochemical Interactions	Novel perspectives were provided in terms of the impacts of compaction on soil microbial communities and greenhouse gas (GHG) emissions, as well as C cycling in tropical soils and peatlands. Effects of compaction on methane and carbon dioxide fluxes were found in studies describing the relationship between soil physical condition and environmental effects in oil palm.
2021-2024	Precision Agriculture and Integrated Management	New developments The focus of the latest research is on combining non-destructive detection, geostatistics and precision farming technology to control compacted zones spatially and temporally attention is given to conservation farming management practices and coupling them with soil amendments such as biochar, organic mulches and cover crops in order to revive the physical, chemical and biological properties of the soils so as to ensure sustained productivity. In addition, new studies are examining chemical and biological resilience to soil compaction in different tropical soils.
2025	Conclusion Continued Research Follow-up on Sustainable Crop and Soil Management	Expected research Expected research plans to use precision technologies and integrated crop production management strategies to improve soil and crop health. There is focus on harmonizing old and new approaches to improve efficiencies of resource utilization, climatic change adaptation and long term sustainability of oil palm estates via integrated soil physical, chemical and biological management.

8. Agreement and Divergence Across Studies

The studies reviewed consistently cite mechanisation and heavy machinery trafficking as the primary cause of soil compaction in oil palm land. This phenomenon, in which the bulk densities is sufficiently increased and the porosity reduced by limiting the free movement of water into the soil mass, changes the physical characteristics of soils and confines plant roots.

That said, the effect of compaction on oil palm productivity is not so clear-cut. In some studies, clear yield reductions are reported while in others adaptive responses such as increased tertiary root growth that may allow sustained or improved production under certain scenarios are noted. This diversity illustrates the influence of soil type, moisture and management history on crop response to compaction.

With regards to management practices, the value of operations such as subsoiling, cover cropping and controlled traffic farming is generally well acknowledged. But their effectiveness depends on the context, and there’s no single size that fits everyone. Likewise, despite the observation of shifts in soil microbial community and chemical properties under compaction stress, the specific path forwards to plant performance and long-term sustainability of soils is not clearly spelled out.

Overall, there is consensus in the effects of soil compaction on physical factors, some degree of consensus regarding mitigating actions and continued debate about biological interactions and yield effects. This emphasizes the requirement of place-based interdisciplinary research taking into account soil physical, chemical and biological processes to manage oil palm plantations sustainably.

Comparison Criterion	**Studies in Agreement**	**Studies in Divergence**	**Potential Explanations**
Causes of Soil Compaction	Many scientific papers agree that the soil compaction in oil palm plantations is mainly caused by mechanization, circulation of heavy machines and reiteration of fieldwork (Caliman, 1990); (de Camargo et al., 2024); (Yahya, 2010); (Kayombo & Lal, 1993); (Biazatti et al., 2022). Furthermore, the soil physical texture and moisture content play important roles in its compaction response (Usaborisut & Ampanmanee, 2015); (Sato et al., 2017).	Some research initiatives highlight additional factors, such as soil acidification and the chemical changes that intervene in the compaction phenomenon, especially when considering ferrallitic sandy soils, which are very peculiar (Caliman et al., 1987). Also, peatland soils are known for their specific response to compaction that is closely related to their moisture condition and the quality of peat as a medium (Busman et al., 2021; Samuel & Evers, 2023).	The differences in the factors of soil compaction may be explained by variations of soil types such as ferrallitic, clayey, peaty, and regional climatic conditions and to a different mechanization degree on these farming systems.
Effects on Yield and Root Growth	Many scientific publications agree that soil compaction has limited root expansion and altered root architecture by reducing mainly the biomass of the primary roots, but in some cases led to a stimulating effect on the finer secondary roots (Yahya et al., 2010a, 2012); (Yahya, 2010); (Biazatti et al., 2022). In addition, compaction usually decreases water and nutrient absorption thus possibly reducing the overall yield (Bhatt et al., 2024); (Satriawan et al., 2016).	On the contrary, some researchers argue that oil palm tolerates compacted soil condition with an outstanding ability to sustain or even increase FFB yield under certain conducive soil conditions as you can see in Bernam series (Yahya et al., 2010b, 2012; Zuraidah, 2019); (Yahya, 2010). The effects on yield may become second-hand and pass through water-deficiency which the consequences of soil compaction cause.	The different yield responses are likely to be a result of variation in soil series, severity of compaction over the course of the experiment, length of treatment with compaction and specific physiological reactions taken by plants.
Soil Physical Property	It is well accepted by	Some works reveal differences	The magnitude of variability in

Comparison Criterion	Studies in Agreement	Studies in Divergence	Potential Explanations
Alterations	researchers that soil compaction increase bulk density, decreases total porosity and macroporosity size and increases penetration resistance; therefore hydraulic conductivity and infiltration rate tend to be significantly reduced (Bhatt et al., 2024; de Camargo et al., 2024; Yahya et al., 2011); (Yahya, 2010). These changes have important consequences on the root-zone state as well as available water.	in other specific observations such as an increase in both mesopores and micropores or changes in pore reconfiguration, which do not correspond to such uniform decrease across the entire pore range (Yahya et al., 2011, 2012). Moreover, the impact of compaction can be limited to surface layers, with relatively little effect on subsoil properties (Sato et al., 2017; Yahya et al., 2009).	these properties depends on different factors, such as soil texture, the depth in which compaction takes place, and how it was measured (i.e., penetration resistance or micromorphology) and years of exposure to mechanization.
Effectiveness of Mitigation Strategies	Mechanical deep tillage is often recommended as a practice to disturb soil compaction layers, which will then stimulate better root growth and enhance yield (Caliman, 1990; Caliman et al., 1990). Furthermore, the bio-species use (cover crops) and the application of organic source amendment are known to contribute positively to soil structure modification and enhanced biological activity that may aid compaction related problems mitigation (Bhatt et al., 2024); (Moradi et al., 2015); (Vikraman et al., 2025). The application of the controlled traffic farming is also an effective approach to reduce the compaction depth and fuel consumption in agricultural work (Benetti & Sartori, 2023); (Misiewicz et al., 2022).	However, while the mechanical loosening methods have their merits, they can also be short-lived in cases of poor traffic control or where there is some hitches in practical logistics towards controlled traffic farming implementation and several researches (Benetti & Sartori, 2023); (Kayombo & Lal, 1993) reported constraints of the mechanical loosening tools. Several studies have shown that the long-term effectiveness and suitability of different mitigation measures may greatly vary according to soil and specific management systems employed (Sung et al., 2011).	There are wide ranging outcomes that depend on various factors, including local conditions of soil, the size or intensity of farm operations, the level of mechanisation employed and how mitigation methods connect to broader management.
Soil Microbial and Chemical Responses	It is widely recognized that when soil becomes compacted, the resulting changes in microbial community populations actually favor anaerobic microorganisms or those with saprotrophic lifestyles but at the expense of microbial diversity and the efficiency of nutrient cycling (Bhatt et al., 2024; Frene et al., 2024; Ishak et al., 2024). Chemical changes upon compaction involve decreases in nutrient availability and, in	Nevertheless, an incomplete comprehension has been detected regarding the underlying dynamics of these effects on microbial and chemical parameters in connection with plant performance (Caliman et al., 1990); (Ishak et al., 2024) since some studies have obtained restricted or uncertain results from such compaction-effects associations. The compaction dynamics of peat soils are complicated and may	This variation in effect is due to the differences in soil types (i.e. mineral versus organic soils) used, measurement techniques utilized, temporal scales involved, and how much biological and chemical interactions are examined under soil compaction conditions.

Comparison Criterion	Studies in Agreement	Studies in Divergence	Potential Explanations
	some cases, reduction of soil pH (Caliman et al., 1987); (Pérez-Sato et al., 2023). Such alterations can be harmful for the growth of plants and soil as a whole.	greatly affect greenhouse gas emissions, differing from its behaviour in mineral soil (Busman et al., 2021; Samuel & Evers, 2023).	

9. Theoretical and Practical Implications

9.1. Theoretical Implications

The synthesis of current research highlights a complex and nuanced relationship between soil compaction and oil palm productivity, challenging the traditional assumption that compaction uniformly reduces yield. Evidence suggests that moderate compaction may not necessarily limit, and in some cases can even enhance, production in certain soils, such as the Bernam series, due to adaptive root morphological changes and altered soil pore distributions (Yahya, 2010); (Yahya et al., 2012; Zuraidah, 2019).

Key soil physical properties such as bulk density, porosity, and penetration resistance, remain critical determinants of root growth and function, yet their impact on yield is moderated by temporal and spatial variability in soil moisture and compaction intensity. Concepts such as Least Limiting Water Range (LLWR) and Water Stress Days (WSD) provide dynamic frameworks that better capture compaction impacts than static measures like bulk density alone (Sato et al., 2017).

The role of soil microbiota and biochemical processes under compaction stress is increasingly recognized. Shifts in microbial community composition affect nutrient cycling and plant-microbe interactions, suggesting that biological responses are integral to understanding compaction effects (Bhatt et al., 2024; Frene et al., 2024). Advances in geostatistical and non-destructive measurement techniques further enhance theoretical modeling, enabling precise mapping of compaction hotspots and their correlation with crop performance (de Camargo et al., 2024); (Molua et al., 2023); (Chong & Chung, 2006).

Integrating soil physical, chemical, and biological parameters into a holistic framework aligns with emerging theories that emphasize interconnected soil functions in sustaining productivity under stress. Observed adaptive root responses, including increased tertiary and quaternary root growth, support theories of phenotypic plasticity, highlighting the importance of root architecture in mitigating compaction effects (Vikraman et al., 2025; Yahya et al., 2010a, 2012).

9.2. Practical Implications

Management-wise, means of alleviation have to be standardized according to soils and environmental situation since soil compaction effects vary depending on texture and moisture regimes. Mechanical operations such as subsoiling prove successful in reducing compacted layers and enhance root penetration, especially with sandy ferrallitic soils (Caliman, 1990; Caliman et al., 1987, 1990)

Controlled traffic and machinery optimization mitigate compaction depths without compromising operational productivity, resulting in emission savings (Benetti & Sartori, 2023); (Misiewicz et al., 2022). Biological practices such as organic amendments, cover crops and mulching use of empty fruit bunches (EFB) also promotes soil structure, water holding capacity for exchange with microbes which are practical for fertility improvement and alleviation of compaction (Moradi et al., 2015); (Sung et al., 2011).

Illustrative examples of soil compaction alleviation strategies in oil palm plantations are presented, encompassing mechanical subsoiling (Figure 3), controlled traffic systems (Figure 4), and biological approaches such as mulching with empty fruit bunches (EFB) and the use of cover crops (Figure 5 & 6). These practices have been widely reported to enhance soil structure and promote root development under compacted soil conditions.

Technology in precision agriculture, based on geospatial mapping and sensor-based monitoring, supports location-specific evaluation of soil and interventions specifically adapted to individual sites, maximizing resource utilization while reducing soil attrition (de Camargo et al., 2024); (Dukat et al., 2025); (Shaheb et al., 2022). Policy support for holistic soil capital management can be achieved by encouraging conservation agriculture and precision farming that facilitate sustainable soil health and productivity (Kumar et al., 2025); (Legoupil et al., 2015).

Finally, knowledge of the time- dependent nature of soil moisture as well its interaction with compaction stresses demonstrates the requirement for real- time soil monitoring to guide irrigation and traffic management decisions in order to sustain yield stability across a production cycle (Sato et al., 2017).

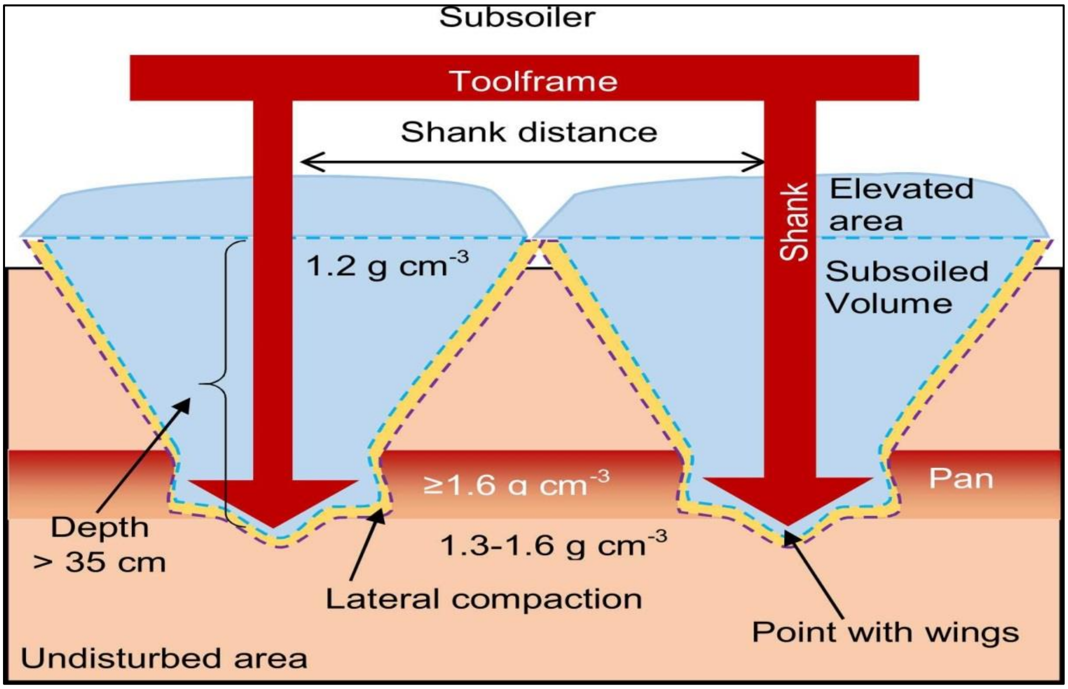

Figure 3. llustrative example of soil compaction alleviation through mechanical subsoiling. Phy-subsoiling is designed to mechanically destroy dense and compacted layers or horizons, increase the volume for [root growth](), and improve the conditions for water penetration and storage, nutrient availability, and aeration. Source: Illustration based on (Ning et al., 2022)

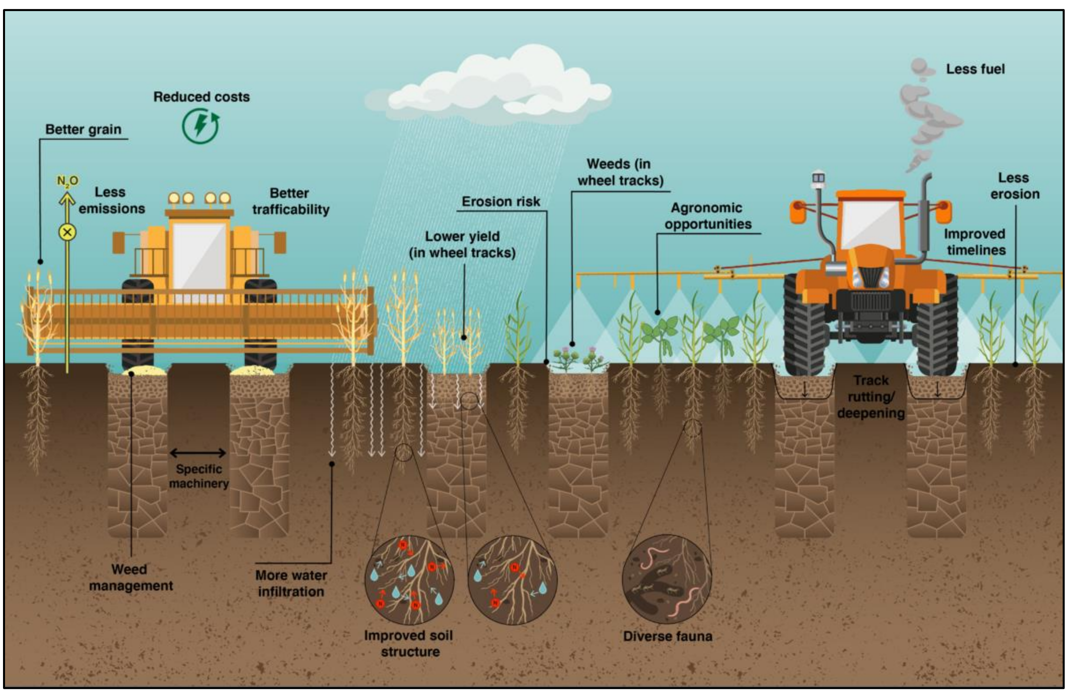

Figure 4. llustrative example of soil compaction alleviation through controlled traffic system. Source: https://soilqualityknowledgebase.org.au/controlled-traffic-farming (accessed 2025)

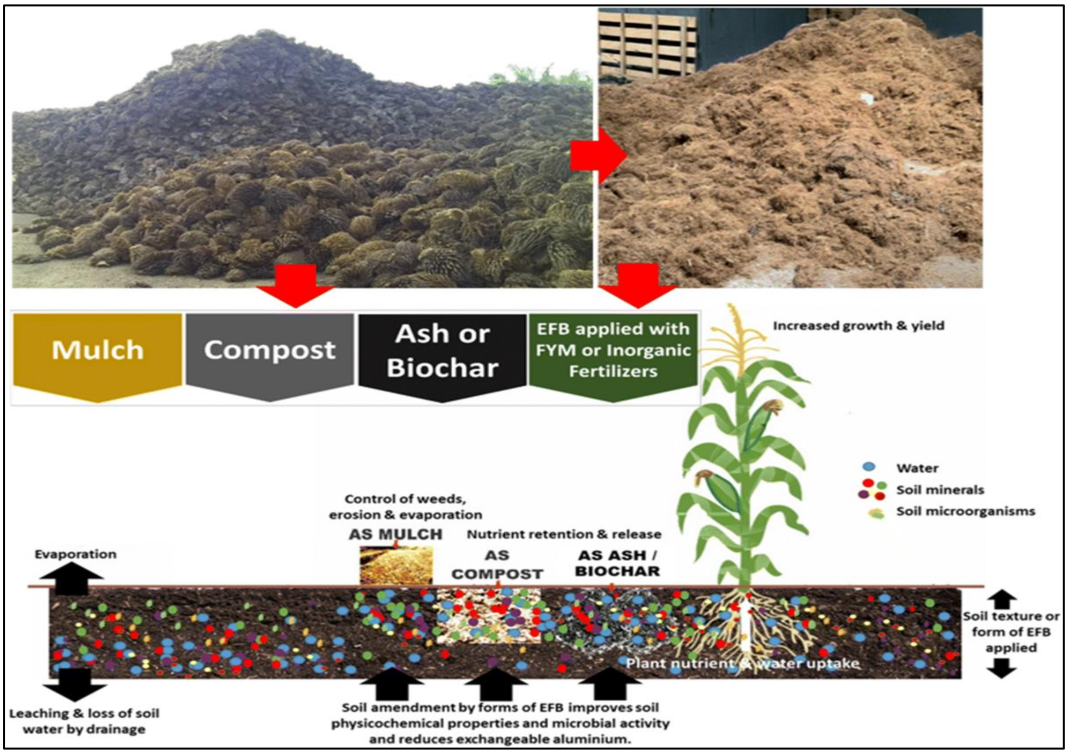

Figure 5. llustrative example of biological soil compaction alleviation through empty fruit bunch (EFB) mulching. Source: Illustration based on (Adu et al., 2022)

Figure 6. llustrative example of biological soil compaction alleviation through cover crops in oil palm plantations. Source: https://akvopedia.org/wiki/Sustainable_Oil_Palm_Farming_/_Establishing_a_ground_cover (accessed 2025)

10. Limitations of the Literature

Area of Limitation	Description of Limitation	Papers which have limitation
Geographic Bias	A great majority of its studies mostly focus on a particular region, such as Malaysia, Côte d'Ivoire and Brazil. This geographical focus, of course, implies that the external validity of our findings may be uncertain in other tropical soils and climates. Therefore, this geographical limitation to the present study limits the application of the results and has low implications for oil palm growing regions with different environmental characteristics.	(Caliman, 1990); (Yahya et al., 2012); (de Camargo et al., 2024); (Caliman et al., 1990); (Yahya, 2010); (Sato et al., 2017)
Limited Temporal Scope	Many studies with relatively short to medium term follow-up, usually around 6 years. Such small-scale temporal resolution might not capture the long-term development of soil compaction and the resulting impact on yield. This time limitation drastically limits the assessment on sustainability and cumulative impacts that may be build up during a lifetime of an oil palm plantation.	(Yahya et al., 2012); (Yahya, 2010); (Yahya et al., 2010b, 2010a)
Inconsistent Yield Responses	Paradox in compaction and yield response of oil palm: a Pursuit Through Lab to the Soil. While some have documented beneficial effects, and others have reported negative or null impacts, the net effect of compaction on productivity remains ambiguous. This discrepancy impedes clear recommendations and leaves stakeholders in confusion around what is effective.	(Yahya et al., 2012; Zuraidah, 2019); (Yahya, 2010); (Yahya et al., 2010b)
Methodological Constraints	Variability of measurement methods, including penetrometry, bulk density determination, geostatistcs and a lack of standardised protocol between measurements means that the comparability of results among different studies is limited. This methodological variation finally constrains the strength of the conclusions reached on the extent of soil compaction and its spatial variability, which complicates result interpretation.	(de Camargo et al., 2024); (Molua et al., 2023); (Yahya et al., 2011); (Chong & Chung, 2006)
Insufficient Microbiome Focus	There is also an alarming gap in the literature regarding proper investigation of interaction among soil compaction, soil microbes and plant physiological response. This lack of attention has left significant gaps in biological mechanisms, which could otherwise have important implications for the development of effective mitigation strategies to reduce the impact of soil compaction.	(Bhatt et al., 2024; Frene et al., 2024; Ishak et al., 2024)
Underrepresentation of Peat Soils	There is, however, a remarkable lack of studies on the impact of soil compaction in tropical peat soils on which many oil palm areas depend critically. This neglect severely restricts knowledge of the distinct physicochemical properties and ebullition dynamics that take place under compression in such sensitive ecosystems.	(Busman et al., 2021; Samuel & Evers, 2023)
Limited Evaluation of Mitigation Strategies	Despite the recognition of various mitigation	(Caliman, 1990); (Benetti &

Area of Limitation	Description of Limitation	Papers which have limitation
	measures in the literature, there has been limited empirical testing examining which are more effective than others under field conditions. This gap hinders the generation of evidence-based recommendations for sustainable soil management in oil palm plantations and thereby result as inadequate guidelines to stakeholders on effective kind of strategies.	Sartori, 2023); (Moradi et al., 2015)
Lack of Socioeconomic Considerations	A strong deficiency is that only few studies are including the economical aspects of precision agriculture and compaction mitigation technology take up. The practical application and scalability of the proposed interventions, especially in smallholder as well as commercial plantations are crucially ignored because this limitation reduces any possible broad spread implication of promising starting points for curative actions.	(Dukat et al., 2025); (Misiewicz et al., 2022)

11. Gaps and Future Research Directions

Gap Area	Description	Future Research Directions	Justification	Research Priority
Soil compaction depth and temporal dynamics	Most research efforts focus mostly on the upper layers of surface soil, in the 0-10cm depth level, thus neglecting to acknowledge the importance of deeper soil which is essential for a healthy root development and long term consequences of soil compaction. Moreover, the amplitude swings and complex dynamic recovery behavior following disturbance of these soil horizons have been poorly studied and deserve further attention.	Long term measurements of soil compaction at several depths (>30 cm) over several years to follow up the compaction processes in oil palms planting.	Knowledge of deeper compaction dynamics is required to support sustainable growth of roots as deep soil compaction restricts the uptake of water and nutrients (de Camargo et al., 2024; Sato et al., 2017; Yahya, 2010).	High
Mechanisms of root response to compaction	Contradicting evidence is available on root biomass decrease or yield retention and little know on the mechanisms behind	Combine physiological, biochemical and molecular studies of oil palm roots grown in differing degrees of compaction to understand adaptation.	It is important to better understand root compensation for compaction stress in the context of long-term sustainability and management (Yahya, 2010; Yahya et al., 2010a, 2012)	High

Gap Area	Description	Future Research Directions	Justification	Research Priority
	root modifications.			
Interactions between soil compaction and soil chemical impacts	Very little is known about the interaction between compaction and soil acidification, cementation and nutrient status in tropical ferrallitic soils.	They studied of compaction and chemical alterations (e.g., pH shifts, aluminum hydroxide precipitation) on soil fertility and root health in oil palm.	Chemical changes might inhibit nutrient uptake, productivity and soil health (Caliman et al., 1987); (Ishak et al., 2024).	Medium
Involvement of soil microbiota in stress from and relief of compaction	Dynamics of microbial communities have been poorly linked to soil physical changes, with mechanisms behind microbiota mediated plant responses remaining enigmatic.	Use metagenomics and functional studies to define the microbial shifts during compaction and trial interventions.	There are other potential roles of microbial communities such as in nutrient cycling and plant resilience, which if understood, could help us improve our mitigation strategies (Bhatt et al., 2024; Frene et al., 2024; Ishak et al., 2024).	High
Long-term effectiveness and cost-effectiveness of mitigation measures	Studies are limited and typically concern short-term consequences; economic evaluations of interventions are rare.	Conducts multi-year field trials combining mechanical, biological and agronomic approaches with cost-benefit analysis.	Sustainable acceptance requires long-term benefits and economic viability for the plantation operators (Caliman, 1990; Caliman et al., 1987); (Benetti & Sartori, 2023); (Kayombo & Lal, 1993).	High
Variability of Soil Strength and Site-Specific Soil Management	Narrow adoption of precision agriculture for compaction management in plantings.	Design sensor-based compaction mapping/management schemes using precision agriculture technologies.	Spatial variation reduces the severity of compaction and efficiency of its control; site-specific management is useful for more efficient resource utilization (Chong & Chung, 2006; de Camargo et al., 2024; Shaheb et al., 2022).	Medium
Impact of compaction on methane and nitrous oxide emissions from peat soils	Overlooked compaction response of carbon fluxes in tropical peatlands converted to oil palm.	Perform field experiments on CO_2 and CH_4 fluxes at different compactions of peat soils.	Compaction of peat affects carbon dynamics, and thus the climate influence, by plantations; this is imperative for sustainable management (Busman et al., 2021; Samuel & Evers, 2023).	Medium
Soil physical, chemical and biological management integration	Since most methods only consider the strategies of physical compaction, they are not combined with chemical and biological amendments.	Formulate comprehensive integrated programmes for soil management comprising the physical loosening, chemical intervention and biological stimulation.	Soil resilience, fertility and crop productivity may be improved through holistic management (Uttran et al., 2023); (Mamatha et al., 2024); (Vikraman et al., 2025).	High
Validation of methods	Differences in	Develop standard	Standardization enhances	Medium

Gap Area	Description	Future Research Directions	Justification	Research Priority
for assessing compaction	measurement depths or techniques, also make the comparisons among studies not feasible.	procedures for soil compaction monitoring, as depth profile and time series.	quality of data and provides support for evidence based recommendations (Molua et al., 2023); (Usaborisut & Ampanmanee, 2015).	
Influence of Environmental Factors on Compaction Evolution	Incomplete investigation of geological parameters influencing compaction development and extent.	Examine the combined effects of mechanization with soil moisture, patterns of rainfall and land topography on compaction in oil palm estates.	Environmental context also assists in adaptive management (Megayanti et al., 2022); (Bhatt et al., 2024; Sato et al., 2017).	Medium

12. Overall Synthesis and Conclusion

Studies of soil compaction in oil palm plantations cite the intensive mechanization (in particular the use of heavy vehicles) as a major factor. Both soil textural class and moisture condition affect vulnerable, the sensitive sandy or clayey soil soils responded differently. Conventions, such as bulldozing and repeated applications of chemicals exacerbate compaction by creating layers compact that impede root growth. Heterogeneity in plantations is typically poorly captured, precluding management.

Soil compaction causes an increase in soil bulk density and a decrease in soil porosity, but its influence on the crop yield is difficult to be determined. Oil palm may acclimatize through increased root growth, stabilising or even increasing FFB yield under some circumstances. Yet, compaction can govern nutrient and water availability, biomass production as well as disease susceptibility, suggesting long-term effects beyond crop yield.

Mechanical treatments such as subsoiling and deep ripping can dislodge compacted layers and stimulate root growth. Biological practices (e.g. cover crops and organic amendments) also enhance physical soil properties and beneficial microbes. Agronomic techniques, such as controlled traffic farming and precision agriculture, also can reduce compaction issues (though the economic sustainability needs further examination).

New studies also indicate that compaction alters soil microbiota and chemistry by promoting anaerobic communities, disturbing nutrient cycles and greenhouse gas emissions. Secondary damage done by acidification and the accumulation of aluminum and iron compounds also diminishes soil quality, although the association between these changes and plant performance has been little studied.

To conclude, integrated, site-specific approaches involving mechanical, biological and agronomic measures are essential for a sustainable management of soil compaction. Future studies should integrate physical, chemical and biological soil health and incorporate long-term monitoring of the effectiveness of mitigation measures to sustain productivity and resilience of oil palm plantations.

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