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*Review*

# Effects of Liming on Soil Properties and Its Roles in Increasing the Productivity and Profitability of the Oil Palm Industry in Malaysia

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**Abstract:** As global demand for edible oil increases, palm oil-producing countries in Southeast Asia are experiencing a rapid expansion of agricultural land for industrial oil palm cultivation by converting existing agricultural lands and some tropical rainforests; however, soil acidity and nutrient depletion are two major constraints in oil palm cultivation in the tropics. Several factors may cause soil acidification, including natural processes, industrial pollutants and extensive agricultural production. Soil acidity increases the leaching of many essential plant nutrient elements and the availability of toxic elements by modifying various geochemical and biological reactions in the soil. Even though acidic soil is less fertile, the productivity of tropical soil is among the highest in the world once the chemical constraints are removed by applying a sufficient quantity of lime and fertilizers. Lime is a widely used alkali to improve soil fertility by retaining nutrients, increasing soil biota, decreasing heavy-metal availability and potentially achieving resistance against *Ganoderma* disease at oil palm estates. Liming materials are not simple compounds with consistent chemical properties; thus, selecting the appropriate lime must be based on soil type and price compared to the products neutralizing value, composition, and fineness. Since the primary aim of liming is to improve soil pH, numerous reviews have been reported on the impacts of soil acidification, nutrient deficiencies and heavy-metal toxicity; however, no extensive review has been published that discusses the effects of liming on oil palm growth and yield. It is not enough to emphasize just soil impacts alone, and a thorough assessment must also be given on crops (oil palm) and soil biodiversity. This review synthesizes current understanding and introduces a holistic approach to provide insights into the far-reaching effects liming has on the biogeochemical properties of tropical soil and oil palm crops.

**Keywords:** liming; oil palm; soil acidity; soil chemical properties; soil microbiome; heavy-metals toxicity



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## 1. Introduction

The rising worldwide demand for palm oil has prompted an expansion in agricultural land dedicated to industrial oil palm cultivation [1,2]. This industrial expansion in the major palm oil-producing and exporting countries, such as Malaysia in Southeastern Asia, has resulted in massive conversion of existing agricultural lands and deforestation of tropical rainforests [3,4]; however, soil acidity and nutrient depletion are two major constraints in oil palm cultivation in tropical regions [5–8]. This is primarily because acidic soil increases the leaching of many essential plant nutrient elements and the availability of toxic elements by modifying various geochemical and biological reactions in the soil [9–12]. Several factors may affect soil acidification, including natural processes, industrial pollutants and extensive agricultural production [13,14]. More specifically, agricultural expansion alone has acidified more than half of the world's farmland, mainly due to monoculture cultivation and the overuse of synthetic fertilizers [10,11]. Liming became a standard agricultural practice used to overcome these limitations and achieve maximum yields of all crops cultivated in acidic soils worldwide [11,15,16]. Lime or liming material is capable of altering numerous geochemical and biological properties of soil, and it provides a variety of benefits [10,16]. For example, it reduces soil acidity, solubilization of hazardous elements, namely aluminum (Al) and manganese (Mn). Besides, it aids in the rise of calcium (Ca) and magnesium (Mg) levels and the availability of phosphorus (P) and molybdenum (Mo), which plays a crucial role in plant healthy development [6,16,17]. Furthermore, it encourages the proliferation of microorganisms already present in the soil and facilitates the formation of a more extensive root system, increasing the plants' ability to absorb water and nutrients from the soil [10,11]. In addition to the chemical and biological characteristics changes of soil, liming also leads to changes in physical characteristics. These changes in soil characteristics depend on the interaction of numerous other factors, including climate, soil type, and intrinsic soil properties [5,10,18].

Agricultural lime is a naturally occurring mineral that contains mainly Ca compounds capable of neutralizing soil acidity. These minerals include calcium carbonate ($CaCO_3$), hydrated lime ($Ca(OH)_2$), calcium oxide (CaO), and slag lime ($CaSiO_3$) [16,19]. Adding liming materials helps to reduce soil acidity by neutralizing acid reactions in the soil. The carbonate component reacts with hydrogen ions present in the soil solution and raises the soil pH; it is the most commonly utilized long-term technique of soil acidity amelioration, and its effectiveness has been thoroughly established in the literature [9]. Although limestone mainly consists of $CaCO_3$, magnesium carbonate ($MgCO_3$) is often replaced over time as a secondary component. Lime, which contains both $CaCO_3$ and $MgCO_3$, is also known as dolomite ($CaCO_3.MgCO_3$). Limestones are remarkably pure, with less than 5% chemical impurities [20,21]. Agricultural liming materials are made by crushing limestone rock because limestone rock is less soluble in water, and grinding into fine particles increases solubility [20]. Application of limestone in highly acidic soil has been standard practice in agriculture since ancient times [22]. It is documented that the Romans employed lime 2000 years ago to compensate for 'source/acidity' on agricultural soil [23,24]. As the global climate changes, effective, sustainable, and ecologically friendly agricultural production methods are required in conventional agriculture. Lime is the least expensive and widely used alkali in agriculture since limestone deposits are extensively available globally, and a large percentage of the population has easy access to this material [16,17].

Oil palm plantations are intensively managed agricultural enterprises rapidly dominating the tropics [3,25,26]. Oil palm monocultures have been the center of criticism by various environmental agencies because of their decreased biodiversity compared to the forests they historically replaced and their detrimental effect on ecology [3,27]. Sustainable agricultural practices are essential for increasing palm oil output on acid soils for agronomic, economic, and environmental considerations [28]. Sustainable agriculture can be described as a method that improves the environment and the resource base on which agriculture relies over time, meets basic food and nutrients requirements, is economically feasible, socially acceptable, and improves the quality of life for farmers and communities [3,27,29]. In 2020, the world's population surpassed 7.6 billion, with projections indicating it will reach 8 billion by 2025 and over 9 billion by 2050; as a result, further increases in food production are needed to satisfy this demand [30,31]. Adequately limed soils improve oil palm cultivation sustainability by increasing crop yields, lowering production costs, and reducing environmental pollution [5].

Since the primary aim of liming is to improve soil pH, numerous reviews have been reported on the impacts of soil acidification and liming on nutrient deficiencies and heavy-metal toxicity; however, no extensive review has been published that discusses the effects of liming on oil palm plantation and yield. It is not enough to emphasize just soil impacts alone, and a thorough assessment must also need to be given on crops (oil palm) and soil biodiversity. This review aims to assess the effects of liming on soil biogeochemical properties and oil palm growth in tropical soil. The review first assesses the current liming management practices at oil palm plantations; it then critically investigates the response of several essential soil biogeochemical processes introduced by liming application with subsequent implications for oil palm yield and resistance to diseases. Finally, it summarizes important findings, highlights areas of ambiguity for liming effects, and identifies critical topics for future research on liming impacts on the oil palm plantation.

## 2. Oil Palm Industry in Malaysia

Malaysia has ideal climatic conditions for oil palm crop cultivation which fostered a rapid expansion of the oil palm industry [2,3,32]. The optimum climatic conditions for oil palm cultivation are a relative humidity of at least 85%, an average of 5 h of sunlight each day, and at least 2000 mm annual rainfall spread uniformly throughout the year with little or no dry season to achieve optimal growth and production [2,33,34]. In addition, steady average temperatures between 24 °C and 28 °C appear to have optimal conditions, with seasonal fluctuations of less than 6 °C. Average temperatures below 17 °C will reduce growth by more than half, and no growth will occur at maximum daily temperatures of 15 °C. The crop usually thrives at altitudes below 400 m in tropical lowlands [2,34,35]. Therefore, oil palm cultivation is the best option for Malaysia, both geographically and economically. In 1917, in Tenamaran Estate, Selangor, Malaysia, began its first commercial palm oil production [36,37]. Oil palm planting statistics reveal that Malaysia only had 54,000 hectares of oil palm plantation area in the 1960s. The cultivated area of oil palm has risen exponentially since then, and in 2020, the oil palm plantations occupied 5.87 million hectares of Malaysian land [38]. Malaysia currently ranks second at global palm oil production after Indonesia, making the oil palm industry a cornerstone of the Malaysian economy [28,38]. In Malaysia, *Elaeis guineensis* is primarily cultivated, a hybrid between the *Dura* and *Pisifera*. Although oil palms may live up to 200 years, the average economic lifespan of an oil palm tree is 25–30 years. Plantation usually replants after about 25 years once the yield of fresh fruit bunches (FFB) starts to decrease and once the average height exceeds approximately 10 m; this is when harvesting becomes economically unfeasible [2].

Palm oil has evolved to be the world's most significant oil produced and consumed. The world population has increased, leading to further demand for palm oil production [3]. The use of palm oil and palm kernel oil has risen exponentially by 69% and 56%, respectively, in the last ten years [39]. More farming land and rain forest in Malaysia are converted to oil palm plantations to meet this increasing global demand. According to the Malaysia Palm Oil Board (MPOB), in 2019 [40], total Malaysian exports of palm oil and other oil palm products amounted to 26.73 million tons, contributing to the total export revenue of approximately USD 17.88 billion. With the rapid advancement of the palm oil industry, sustainability development throughout the sector is extremely difficult. Therefore, there is an interest in incorporating sustainable development task forces within the frameworks of palm oil companies, which include key elements, such as economic, environmental, and social factors [2]. In Malaysia, for example, a Roundtable on Sustainable Palm Oil (RSPO) has been formed to regulate the sustainability of the palm oil sector, describing key elements of legal, economic viability, environmental, and public policy via policies known as RSPO Principles and Criteria [2,27,41]. Although this sector is financially secure, it may enhance its sustainability by improving various aspects of oil palm cultivation and mill processing [28].

### *2.1. Soil Characteristics in Malaysian Oil Palm Plantation*

In Malaysia, oil palm plantations are mostly established in tropical Oxisols and Ultisols [7,10,42]. The Oxisols and Ultisols are characterized as highly acidic, high Al saturation, high P fixation capacity due to heavy rainfall that causes excessive loss of the basic cations, and they cannot sustain high production of oil palm crops [10,18,29]. Even though acidic soils are less fertile, the productivity of tropical soil is among the highest in the world once the chemical constraints are removed by applying a sufficient quantity of lime and fertilizers [7,42,43]. Being one of the highest biomass producers among the C3 plants, the oil palm needs an excessive amount of nutrients to support vegetative growth and fruit production [2]. For these excessive demands, even fertile soils cannot sustain the production of high-yielding oil palm for more extended periods [43]. Thus, proper soil management practices are crucial to maintaining appropriate oil palm nutritional status and high yields [28].

### 2.2. Soil Management Practices in Oil Palm Plantation

Proper management of plant nutrients is an integral part of commercial oil palm production. In recent years, a substantial breakthrough has been made in determining the nutritional needs of oil palm crops [2,43,44]. While nutrient demand indicates a plant's nutrient needs, the supply of nutrients is based on the availability of mineral nutrients from the soil, which is influenced by the soil acidity (pH), texture, water availability, plant root density, and nutrient leaching. While some of these factors generally stay constant, others show seasonal patterns based on a specific location [43,45]. Due to these uncertainties, it is very complicated for the oil palm estate to develop a standard fertilization routine for best sustainable soil management practices, ensuring efficiency, effectiveness, and high yield [2]. Traditionally, soil management in most oil palm plantations is done by applying chemical fertilizers around the oil palm tree. In addition, oil palm fronds and empty fruit bunches (EFB) are stacking in the oil palm inter-rows, enhancing soil physical characteristics [30]. Although the direct application of EFB, fronds increase the risks of pests, weed seeds, or parasites spreading into the plantation area. In this context, liming would be the most appropriate method to reduce these risks and improve soil biogeochemical properties, which in return increases oil palm yield [14].

Liming management in oil palm plantations is complex due to regional differences in land use, climates, and management objectives set by oil palm estates; timing application methods, frequency, depth, and timing of liming are essential factors that need to be considered when enhancing efficiency and crop yields at oil palm plantations on acidic soils [14,17,46]. The technique of applying lime is a practical problem that impacts liming efficacy and is determined by the kind of land use; for example, for oil palm plantations, lime may be used as a top-dressing (surface applied) [9,14]. The best method of liming application is prior to crop planting, and it should be spread and mixed uniformly into the soil to maximize its interaction with soil exchange acidity [6]; this will optimize liming effectiveness and crop yields [20]. Caires et al. (2011) [47] assessed the effectiveness of dolomitic lime application on the soil surface. The team concluded that dolomitic lime applied to the soil surface at full or divided rates, or integrated, showed long-lasting impacts on soil acidity, calcium, and sulfur availability. The frequency of liming is primarily influenced by the intensity of farming, the kind of crop planted, and the levels of $Ca^{2+}$, $Mg^{2+}$, Al, and pH of farmland after each harvest.

Although liming has a long-lasting beneficial effect on the soil ecosystem, it is not permanent [14,48]. After many harvesting seasons, $Ca^{2+}$ and $Mg^{2+}$ migrate lower and beyond the reach of roots. Crops take up these elements and, to some extent, are lost through soil erosion, especially in tropical regions. The application of lime should be repeated if the exchangeable $Ca^{2+}$, $Mg^{2+}$, and pH levels fall below the optimal levels [9]. This implies that soil samples should be collected regularly to evaluate changes in soil geochemical characteristics and calculate the frequency with which liming should be performed. A single dose of liming was found to be more beneficial than split dosages yearly [17]. Alvarez et al. (2009) [49] investigated the influence of particle size (2–4 mm, 0.25–0.5 mm, and $\leq$0.25 mm) and frequency of Mg-limestone (single dose or three doses annually) potentially having impacts on the amount of Al in acid Galician soil's soil and liquid phases. After three years of the trial, the plots treated with a single dose of the finest Mg-limestone ($\leq$0.25 mm) had the highest pH value and the lowest amounts of exchangeable. Liming material should be uniformly mixed and incorporated as deeply into the soil to enhance crop root systems in acid soils. Modern agro-machinery allows to trill soil to a depth of 20–30 cm; a depth of more than 30 cm requires additional power and increased labor and energy costs. When it comes to obtaining desired effects, the timing of lime application is critical. Lime should be applied as long ahead of the planting of the crop as feasible to enable it to react with soil minerals and cause substantial changes in the chemical characteristics of the soil [14,17].

## 3. Beneficial Impacts of Liming on Soil Processes in Oil Palm Plantations

In facing global warming, oil palm cultivations demand the implementation of sustainable, efficient, ecologically friendly management practices. Liming is an essential soil management technique in this context since it helps to maximize the production of oil palm crops growing on acidic soils. Liming is the most commonly utilized long-term technique of soil acidity restoration, and its effectiveness has been well established in the literature [50]. Applying lime at an adequate amount leads to numerous biogeochemical changes in the acidic soil that is favorable in increasing crop yields on acid soils (Figure 1).

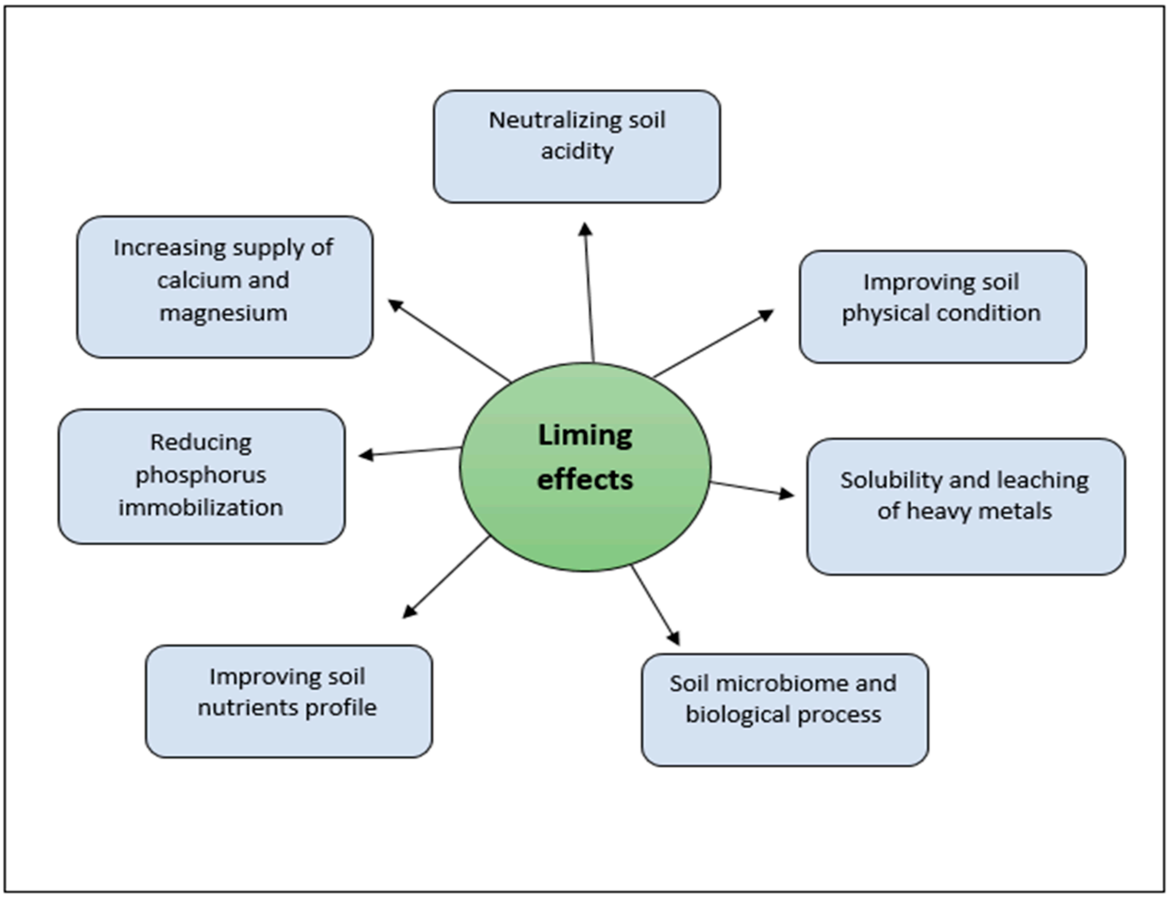


**Figure 1.** Schematic representation of the liming influences on many biogeochemical processes on the acidic soil. Carbonate components present in liming materials react with soil acidic components to raise the soil pH. These in return decrease heavy-metals toxicity, thus improving soil properties (e.g., soil structure, nutrients availability, pH, and soil biota).

### *3.1. Neutralizing Soil Acidity*

Soil pH is known to influence a variety of soil characteristics needed by plants for healthy growth and development (e.g., resistance against diseases, root system, soil microbial activities, availability of nutrients, and rate of photosynthesis), resulting in projected harvests [10,11,45]. Soil acidification processes can be classified into two major categories: (i) by natural causes (e.g., rainfall, nutrients leaching, and decomposition of organic materials) and (ii) by controlled agro-ecosystem through excessive agricultural operations (e.g., application of N-fertilizers and harvest of high-yielding crops) [15]. To neutralize soil acidity and solve the issues associated with soil acidification, liming materials such as calcium carbonate, calcium hydroxide, calcium oxide, dolomite/ground magnesium limestone (GML) are commonly applied to oil palm estates [25,29,51]. A liming material must be able to react with and neutralize hydrogen ions ($H^+$) to decrease the soil acidity to be effective. The most common liming materials comprise calcium or magnesium carbonate $(CO3)^{2-}$ or oxide ($O^{2-}$), which neutralizes $H^+$ and raises the pH value of the soil in a variety of ways [50]. Calcium or magnesium cations (or occasionally both) are present in liming materials, and their presence has a neutralizing effect, displacing hydrogen ions ($H^+$) from the soil solution [14,50].

For calcium carbonate the reaction is:

$$CaCO_3 + 2H^+ \Leftrightarrow Ca^{2+} + CO_2 + H_2O \tag{1}$$

For dolomitic lime the reaction is:

$$CaMg(CO_3)_2 + 2H^+ \Leftrightarrow 2HCO_3{}^- + Ca^{2+}\ Mg^{2+} \tag{2}$$

$$2HCO_3{}^- + 2H^+ \Leftrightarrow 2CO_2 + 2H_2O \tag{3}$$

For Cal-Sil or calcium silicate lime, the reaction is:

$$CaH_2SiO_4 + 2H^+ \Leftrightarrow Ca^{2+} + H_4SiO_4 \tag{4}$$

According to Equations (1)–(4), the acid-neutralizing reactions of lime take place in two stages. The first stage involves the reaction of Ca or Mg with $H^+$ on the exchange complex, with $H^+$ being replaced by $Ca^{2+}$ or $Mg^{2+}$ on the exchange sites, resulting in the formation of $HCO_3$. In the second stage, $HCO_3$ interacts with $H^+$ to produce $CO_2$ and $H_2O$, which raises the pH of the solution. The reaction rate of lime is primarily determined by the soil moisture and temperature and the amount and quality of the liming material. Even though magnesium and calcium are good for soil quality and plant nourishment, but they do not have a direct role in raising pH. Materials containing calcium but no carbonate, such as gypsum, burnt lime, and calcium oxide, will not alleviate soil acidity [19,29]. Selection for liming materials for oil palm plantations should be based on the price compared to the product's neutralizing value, composition, and fineness (Table 1). The neutralizing value indicates how much carbonate or oxide it contains. The higher the neutralizing value, the higher the carbonate or oxide it contains and the greater its value as a liming material.

**Table 1.** Types of commercial liming materials, their chemical composition, neutralizing value, and characteristics [9,24].

| Commercial Name | Chemical Composition | Neutralizing Value (%) | Characteristics |
|---|---|---|---|
| Calcium carbonate or calcitic lime | $CaCO_3$ | 100 | It contains mainly $CaCO_3$ (>30% Ca) and $MgCO_3$ (<5% Mg). Most commonly used agricultural lime. |
| Dolomitic lime | $CaMg(CO_3)_2$ | 95–109 | It typically contains 42% $CaCO_3$ and 53% $MgCO_3$). |
| Calcium oxide or burnt lime | CaO | 179 | It reacts quickly and is hard to manage. |
| calcium hydroxide | $Ca(OH)_2$ | 136 | It reacts quickly and is hard to manage. |
| Slag lime | $CaSiO_3$ | 86 | It reacts quickly and is hard to manage. |

The average soil pH value in the oil palm estates in Malaysia is 4.3; despite this, the oil palm plantations were able to sustain their growth [29]. Increasing soil pH to a level greater than five has been shown to decrease exchangeable soil Al, resulting in increased availability of other nutrients in the soil for plant absorption, which improves overall physical growth and yields for the crop. A significant amount of research has been carried out to investigate the impact of liming on crop productivity and yield. Herviyanti et al. (2021) [52] reported that on tropical Ultisols, the treatment of 450 g Sub-bituminous coal activated with 10% dolomite results in substantial increases in pH, P availability, organic carbon, total-N, and CEC. According to Caires et al. (2015) and Caires et al. (2011) [47,48] the surface lime application under no-till significantly reduced soil acidity in the long-term throughout the soil profile. A similar report was published by da Costa et al. (2016) [6] that after 48 months, surface liming raised the pH of the soil in the surface layers to a depth of 0.20 m, with the effect spreading throughout the soil profile after 60 months of reapplying the lime.

### *3.2. Liming Impacts on Soil Nutrient Processes, Minerals, and Heavy Metals*

To sustain vegetative development and fruit production, oil palm needs large quantities of nutrients [2,45]. In oil palm plantations between 3 to 15 years old, the annual fertilizer requirement for N, P, K, and Mg per hectare can rise up to five times [29]. These elements have various primary functions in plant metabolism, including the formation of chlorophyll, photosynthesis, protein and starch synthesis, cell walls and membrane formation, roots, and meristem growth [2]. When adequate amounts of these nutrients are available for plants, they produce more biomass and fresh fruit bunches (FFB) with high oil content [53]. In Malaysian soil, these basic cations (Ca and Mg) are naturally devoid, and hence, their productivity is considered low [45]. The Malaysian oil palm estates adopted various soil management strategies to overcome these native obstacles, and liming is one of them. In tropical acidic soil, the addition of lime initiates buffering mechanisms that alter the balance of exchangeable cations and the dissolution of Al, Mn, and Fe minerals and the pH of the soil. One of the most significant effects of soil acidity is a rise in the content of Al and Mn, both of which are incredibly harmful to plants [25]. The impact of Mn toxicity seems to be directly linked to the metabolic activities of plants. In contrast, the effect of Al toxicity appears to be expressed primarily as deformity and dysfunction of the root system [54], a condition aggravated by low amounts of soluble calcium in acidic soil.

Several studies indicate that liming can increase the bioavailability of plant nutrients by increasing soil pH. Husain et al. (2021) [45] studied the residual liming effect of $Ca^{2+}$-amendments ($CaO$, $Ca(OH)_2$, and $CaCO_3$) and compared them with $Mg^{2+}$-amendments (dolomite) on highly acidic soils previously planted with oil palm seedlings. Following the findings, it was revealed that $Ca^{2+}$-amendment residues had the ability to lower soil acidity more than $Mg^{2+}$-amendment residues. Calcium hydroxide was the most notable $Ca^{2+}$-addition that increased soil-water pH, soil solution pH, and soluble $Ca^{2+}$ and $K^+$ concentrations. Aini et al. (2021) [25] investigated the mobility and availability of Cd, Zn, and P to oil palm seedlings, as well as their soil phase association, after the soil was supplemented with phosphate rock (PR) fertilizer, palm oil mill effluent (POME), and lime. The team found that in contrast to POME, lime was shown to be a superior amendment for decreasing Cd absorption from PR fertilizer application. With increasing liming rates, the Cd level in the root decreased, and 65% of Cd in the soil was in the immobile phase. The soil pH increased significantly when treated with lime; increasing soil pH reduces metal availability via precipitation. The lime treatment increased pH, which promoted heavy-metal precipitation and increased heavy-metal absorption by variably charged colloids such as organic matter and Fe-Mn oxides, reducing the concentration of accessible metal. Kurniawan et al. (2018) [7] reported that higher base saturation, exchangeable Ca, and accessible P were achieved with the use of mineral fertilizer and dolomite lime ($CaMg(CO_3)_2$). In the surface adsorption, dolomite ($CaMg(CO_3)_2$) presumably replaced soil exchangeable Al and reduced soil exchangeability. In a different study, Panhwar et al. (2020) [55] found that the Ground Magnesium Lime (GML) plus biofertilizer treatment had the lowest exchangeable Al (0.75 $cmol_c\ kg^{-1}$), followed by the Rich Husk Biochar (RHB) plus biofertilizer (0.86 $cmol_c\ kg^{-1}$) treatment. The control treatment has the greatest exchangeable Al of 5.12 $cmol_c\ kg^{-1}$. After the soil was treated with liming additive, either alone or in conjunction with a biofertilizer, the Al content was low.

### 3.3. Impacts on Soil Microbial Communities and Biological Processes

Soil microbial activities can be used as soil quality indicators since they are the second most influential biological agents (after plants) in agriculture [9,23]. These soil-dwelling microorganisms comprise different taxa, such as bacteria, arbuscular mycorrhizal fungi (AMF), actinomycetes, and cyanobacteria [30]. Important characteristics of these microbes include improving root systems, production of organic acids, phytohormones, antibiotics, siderophores, volatile bacterial compounds, solubilization of phosphorus, nitrogen-fixing, carbon cycling, and disease prevention [4,14]. The activities of these helpful microbes can be restricted by the soil's acidity, except for fungi, which may thrive in a broad range of soil pH [9]. The result of this constant communication between the plant and its microbiota makes it feasible to manipulate the microbes present in soil by adequate liming, which can influence the development of the plant's defense against pests and diseases, thereby increasing total yield [55]. Whether applied to tropical soil, lime has been proven to have beneficial effects on the quantity and community composition of virtually all kinds of soil organisms (Table 2).

**Table 2.** Selected examples of how liming affects various soil biota, soil processes, and functional impacts [14,56,57].

| Soil Microorganism | Change in Population | Associated Process | Overall Functional Impacts |
|---|---|---|---|
| Bacteria | Thriving | Decomposition | +ve (nutrient cycling) |
| Rhizobia | Composition change | Nutrient delivery | +ve (nutrient cycling) |
| Arbuscular Mycorrhizae fungi | 1. Thrives between pH 5 and 6, but decreases at pH 7<br>2. Composition change | Nutrient delivery, soil aggregation, antagonist defense | Variable |
| Fungi | Thriving | Recalcitrant decomposition | +ve (C storage) |
| Microarthropods | No effect | Decomposition | Variable |
| Nematodes | Variable | Disease, decomposition, predation | -ve (disease regulation) |
| Earthworms | Thriving | Decomposition, soil aggregation | +ve (nutrient cycling) |
| Pathogens | Decrease | Disease | +ve (disease regulation) |

"+" = Positive; "-" = Negative.

Liming application can change the microbial function on the acidic soil by increasing the soil pH. Lime has been found to enhance microbial activity, change the makeup of the microbial community, and increase the population of acid-sensitive microorganisms and soil respiration when soil acidity restricts microbial development [23]. Liming-induced changes in soil pH have been extensively studied. A study conducted by Panhwar et al. (2020) [55] was designed to evaluate the effects of applying GML and rice husk biochar (RHB), with or without biofertilizer, on enhancing soil biochemical characteristics and the production of rice grown on an acid sulfate soil. The team reported that 30 days after planting, GML combined with biofertilizer generated the highest soil pH of 5.66, which stayed high (5.43) through rice harvest. They also found that using GML or RHB with biofertilizer boosted all bacterial populations. The GML plus biofertilizer treatment had an 8.34 $\log_{10}$ CFU $g^{-1}$ soil bacterial population, followed by the RHB plus biofertilizer treatment (7.23 $\log_{10}$ CFU $g^{-1}$ soil).

### 3.4. Improving Soil Physical Condition

The texture influences the buffering capacity of the soil. Buffering capacity refers to the ability of solid-phase soil components to withstand fluctuations in ion concentrations in solution [8,14]. Tropical soils predominantly made up of iron, aluminum oxide minerals, and kaolinite are known for their low-to-moderate cation exchange abilities but with a high buffering capacity [58]. As a result, tropical soils need a significant quantity of liming materials to increase the pH of the soil. When it comes to soil fertility, the amount of nutrients present in the soil is measured, and soil analysis is often employed as a criterion for making fertilizer recommendations for farming. Liming materials are required in lower amounts if the soil is highly fertile in terms of higher exchangeable $Ca^{2+}$, $Mg^{2+}$, and $K^{+}$. This is due to more significant amounts of these basic cations in the soil, which results in a significantly higher base saturation and a higher pH than with lower quantities of these cations in the soil. In comparison, higher amounts of organic matter in the soil decrease the need for lime, and as a result, humus soils need less lime than other mineral soils [9]. In addition to influencing soil chemical characteristics, liming has a significant impact on the physical property of the soil, such as the structure of the soil that may impact crop yields. Ca in lime, for example, aids in the production of soil aggregates, improving soil structure and, therefore, particle dispersion and flocculation [5,10,11]. It is possible to reduce nutrient leaching losses by altering soil characteristics such as (i) physical characteristics that influence nutrient availability, water holding capacity, and soil density and (ii) biochemical characteristics that reflect nutrient supply and storage due to indirect impact weathering and mineralization. Nutrient leaching is typically minimal in soils with high nutrient availability and water holding capacity but poor water infiltration, such as clay soil. On the other hand, nutrient leaching losses are more common in sandy-textured soils with high soil macroporosity, allowing water to flow more freely [9]. Soil structure affects plant development by influencing water infiltration, percolation, retention, soil aeration, and structural resistance to root growth [23]. Often, liming is suggested to foster earthworm colonization in farmlands. The release of various metabolic compounds and the crawling activity of earthworms directly impact soil structure and macroporosity due to the increase in earthworm activity caused by the lime application [9,13]

## 4. Beneficial Impacts of Liming on Oil Palm Trees

The two major issues in ensuring the productivity and profitability of oil palm plantations are efficient fertilizer usage and soil deterioration [28]. In Malaysian oil palm plantations, a high rate of chemical fertilizers is applied to maintain nutrient availability in the soil year-round to support physical growth and fruit production [11,45]. Furthermore, fertilizer accounts for 40–65% of overall field costs in oil palm plantations [58]. Various liming materials can be used to overcome the problems of low productivity of acidic soil.

### *4.1. Increasing Oil Palm Tree Biomass and Yields of Fresh Fruits Bunches*

Liming improves oil palm crop output mainly via its direct impacts on soil chemical, physical and biological properties, which improves availability and mobility of several plant primary nutrients. Li et al. (2018) [11] explored the role of liming rate, lime application technique, and types of lime on different soil biogeochemical characteristics and crop production based on data collected from 175 published studies worldwide since 1980. The researchers concluded that liming improved crop yield irrespective of environmental or experimental settings. The higher yields induced by liming are highly dependent on crop species, types of lime, application methods, and soil types. Using oil palm seedlings as the experimental subject, Cristancho et al. (2011) [59] researched to evaluate the effects of soil acidity reduction on the plants using GML and dolomite limestone (0, 1.1, 2.2, 3.3, and 4.4 t/ha). Oil palm seedlings were assessed for eight months under nursery settings on selected morphological and nutritional features of hybrid (*Deli duraAVROS pisifera*) and clonal (clone 366) oil palm progenies. The team reported that the increasing GML and dolomite limestone rates substantially impacted soil pH and reduced exchangeable Al. For the majority of the parameters studied, the hybrid oil palm exhibited strong linear or exponential trends, suggesting that the optimum morphological and physiological responses were obtained at 2.5 to 4.23 t/ha with GML and 2.87 to 3.45 t/ha with dolomite limestone, respectively. Positive effects of increasing rates of GML and dolomite limestone were observed on N and Mg uptake. The reduction of soil acidity aided the development of oil palm seedlings. The team came to the conclusion that these findings are significant for the oil palm industry and that they may be used at both the nursery and immature stages.

Similar results were obtained by Herviyanti et al. (2021) [52] while evaluating the sub-bituminous coal (SC) power with dolomite lime to enhance the biogeochemical properties of acidic soil and how it boosts the growth of oil palm seedlings. Using analysis of variance, the researchers revealed that dolomite-activated SC had a very significant impact on the height of the palm oil plant, the number of midribs in the plant, stem diameter, and nutrient concentrations (N, P, and K) in the total biomass of the plant. Compared to the control, the SC activated by dolomite at a dosage of 450 g SC had a statistically significant impact on plant height of 12.33 cm, compared to the control. The impact of dolomite activation on oil palm nutrient absorption is different from when it is not activated. In comparison to other treatments, the 450 g SC dosage had higher P and K concentrations than the other treatments, but N concentrations were the same at the 450 g SC and 300 g SC doses, respectively. Due to the availability of the soil nutrients (C, N, P, K, Ca, and Mg), the plant height increases due to the rise in soil nutrient content. Humic substances combined with lime may enhance the chemical conditions in the root environment, allowing the roots to develop more effective nutrients supplied to be absorbed by the roots, resulting in improved plant development. If adequate nutrients are available during vegetative development, the photosynthetic process will be active, allowing cell division, elongation, and differentiation to proceed smoothly, increasing plant production.

### *4.2. Controlling Oil Palm Tree Diseases*

The mineral nutrition of plants is critical in the management of plant diseases. When compared to nutrient-deficient plants, healthy plants that get a sufficient supply of vital nutrients in an optimal balance are more likely to have fewer diseases [60,61]. In addition to the optimum rate of nutrient administration, a proper nutrient balance is critical for assessing the impact of mineral nutrition on plant diseases [9]. An excess supply of nutrients may cause an imbalance with other nutrients, increasing the likelihood of plant disease outbreaks [62]. There is also a scarcity of extensive research data to evaluate the impact of mineral nutrition on plant diseases that have included both soil scientists and plant pathologists. Existing evidence indicates that liming may positively affect certain diseases while having an adverse effect on others. Calcium has been linked to the development of plant resistance to several plant diseases, including *Ralstonia solani*, *Sclerotium rolfsii*, and *Fusarium oxysporum*, among others [9]. Lime increases Ca, K, N, Mg, Mo, and P availability while decreasing Al, Mn, and Fe availability; indeed, it would be fascinating to see how variations in the availability of these nutrients in the soil influence plant disease and pests.

The Malaysian oil palm industry is constantly threatened by a disease known as Basal Stem Rot (BSR) caused by *Ganoderma boninense*, a white-rot fungi [63–65]. BSR disease continues to undermine the profitability of the oil palm sector and has caused widespread worry worldwide because of the lack of an effective treatment. The capacity of the plant to withstand pathogen invasions and its physiological growth may be influenced by soil pH variations. BSR development in oil palm seedlings as influenced by soil pH levels as a soil-plant pathogen. For decades, low pH (3.7 to 5.0) has been correlated to a reduction in the prevalence of BSR disease in oil palm [66,67]. One of the most popular ways of managing the effects of soil acidity on plants and soil is to increase the pH of the soil. To do this, lime is applied to the soil surface to raise the pH of the soil in oil palm estates. Rahman and Othman (2020) [67] hypothesize that soil pH levels have the ability to inhibit the growth of *G. boninense* in oil palm seedlings in their search to find a resolution of BSR disease development in oil palm. They took soil samples from three distinct locations: forest, *Ganoderma*-infected, and uninfected oil palm plantation sites. Sixty rubber woodblocks were inoculated with *G. boninense* inoculum and used to grow the plant, while pH levels were adjusted using calcium carbonate (pH 4.5 control), pH 5, pH 6, and pH 7, respectively. The findings indicated that all treated seedlings had peak infection incidences during the 4th month and were severe from weeks 8 to 12, with pH-treated seedlings seeing lower infection rates than the control population. pH 6 has a high ability to inhibit the development of BSR illness in the roots of oil palm seedlings that have been infected with *Ganoderma*.

## 5. Recommendations and Implications

In the future, as part of a strategy to promote sustainable and productive agriculture, relentless efforts will be required in Malaysia to ensure proper soil management for the oil palm plantations in terms of nutrient availability in soil, water management, and diseases control. Liming materials cannot be substitutes for N, P, Mg, or any other essential plant nutrients, and it would not be wise to rely only on lime as a single source of soil nutrients; however, over the past decades, we have learned that relying on commercial fertilizers and tillage fully to produce most crops in regions that suffer a severe lime shortage is, similarly, unwise. It goes without saying that acidic soils in Malaysia desperately need the rich organic matter that clover and grass sods might provide, and one of their requirements is lime. This review has assessed many potential liming impacts on a wide range of soil geochemical processes, oil palm growth, and soil biota. There are still several areas where more extensive research is needed. A better fundamental understanding is required in at least two broad areas: (i) at the process level (e.g., biogeochemical processes) and (ii) on the physiology of oil palm trees (e.g., yield and resistance to diseases).

In recent years, there has been significant improvement in our knowledge of the effects of liming on soil microorganisms, which is promising. Additional research is required on the effects on soil biology in general, but notably on plant growth-promoting bacteria, actinomycetes, fungi, nematodes, and arthropod species, across a broader range of environmental variables, particularly in tropical soil. New advances in molecular techniques have made it possible to identify better and comprehend these groupings. Past studies on liming have emphasized the significance of precipitation mechanisms and the formation of ionic bridging. Still, the degree to which this occurs in different soil types is not fully addressed. There is still a lack of understanding of the interactions between elements such as P, K, Ca, N, Mg, and C. Furthermore, not all soil nutrient assessments properly account for the influence of soil pH. There is relatively little research on the effects of liming on soil physical characteristics and structural state while applying different forms of lime in oil palm plantations (e.g., calcium vs. magnesium limes). To address recent concerns regarding soil fertility and the long-term viability of existing nutrient management methods, it is necessary to conduct a more comprehensive investigation of the long-term consequences of liming in oil palm plantations, particularly in nutrient availability, influences of pH soil types, and soil biota.

Further knowledge in understanding the interaction of liming with other management practices used on oil palm plantations is urgently needed. Liming will typically be only one among many management practices, and it is essential to understand which activities have a significant relationship with liming to make appropriate decisions. It is necessary to study the interactions of liming with other essential crop management techniques, such as fertilizer, liming materials, application methods, and monocultural cultivation. There is a tremendous need for a comprehensive assessment of how liming affects both soil and oil palm crops because of the wide-ranging and substantial effects on both soil and crop productivity. The Malaysian government should support the oil palm industry and independent smallholders and encourage the usage of liming material for better soil management. Developing proper soil management techniques incorporated with liming practices will significantly impact the country's stainable agricultural economic development. The government should encourage more sustainable farming by offering special incentives to the local farmers and private sector, and educate them about the benefits of using liming material for proper soil management. Government and privately funded research and development (R&D) activities need to increase to find new opportunities and solutions to current issues related to liming application and its effects on soil and oil palm crops.

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