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REVIEW ARTICLE

Restoring soil health from long-term intensive Robusta coffee cultivation in Vietnam: "a review"

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Abstract

Robusta coffee, a vital cash crop for Vietnamese smallholders, significantly contributes to the national economy. Vietnam is the largest exporter of Robusta coffee, supplying 53% of the global market. However, this success has come at a cost. Decades of intensive Robusta coffee cultivation in Vietnam have led to severe soil acidification and biodiversity loss, favoring soil-borne pathogens. There is a lack of literature analyzing how intensive management causes soil acidification, advances the spread of soilborne pathogens, and the application of soil amendments to address these issues. Therefore, this review explores the causes of acidification, pathogen proliferation, and sustainable amendments like lime and biochar to mitigate these effects. The study synthesizes findings from studies on soil acidification, soil-borne pathogen dynamics, and sustainable soil amendments in Robusta coffee systems. We found that the overuse of nitrogen-based chemical fertilizers to grow coffee is the primary driver of soil acidification, consequently increasing soilborne diseases and the severity of plant diseases. Additionally, the effects of soil amendments as a sustainable solution to reduce soil acidity, enhance soil health, and better control soilborne pathogens. The implementation of sustainable coffee farming systems is strongly recommended to meet the increased demand for safe and green products worldwide. Locally available resources (lime, biochar, and agricultural wastes) present immediate solutions, but urgent action is required to prevent irreversible damage. However, the effects of amendments significantly vary in field conditions, suggesting that further studies should be conducted to address these challenges and promote sustainability.

Keywords Intensive coffee cultivation · Soil acidification · Soilborne pathogen · Agricultural soil amendment

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Contents

1 Introduction

Robusta coffee (*Coffea canephora* var. *Robusta*) dominates Vietnam's agricultural economy, with 650,000 hectares contributing 53% of the global supply (ICO 2022; DCP 2023). However, intensive cultivation practices have led to severe soil degradation, threatening long-term sustainability. Coffee cultivation is primarily concentrated in the Central Highlands (Figure 3), with 90% of the coffee farms being managed by smallholder farmers (Rigal et al 2023).

The shift towards intensive coffee cultivation, particularly the excessive use of nitrogen (N) fertilizers over the past few decades, has been aimed at maximizing coffee yields (Castro et al 2012; Capa et al. 2015), but this has led to adverse agronomic, economic, and ecological consequences, with soil degradation, particularly acidification (lowering of soil pH), and soilborne plant diseases posing significant threats to coffee production (Dung et al 2019; Zhang et al 2022). While N fertilizer application is marginally positively correlated with coffee yield, it has also been identified as the primary cause of soil acidification (Castro et al 2012; Zhang et al 2022). Acidification results in reduced soil pH, increased metal toxicity including aluminum (Al), manganese (Mn), and iron (Fe), and deficiencies in phosphorus (P), calcium (Ca), magnesium (Mg), and potassium (K), consequently impacting soil fertility, plants, and soil microorganisms (Kunhikrishnan et al 2016). Acidification disrupts the balance of microbial ecosystems (Deng et al 2024), leading to a decrease in the overall relative abundances of bacteria and fungi, as well as a reduction in potential beneficial microbes (Zhao et al 2018). Furthermore, acidification has been shown to increase soilborne diseases and the severity of plant diseases while also promoting pathogen establishment (Fagard et al 2014; Martinez et al 2021; Zhang et al 2022) (Fig. 1).

The intensive farming practices adopted in Vietnam led to a 115% increase in coffee yields from 1996 to 2020 (Hong et al. 2017; DCP 2021). However, this approach has resulted in a significant decrease in soil pH and an increase in the occurrence of yellowing leaf diseases. These diseases are caused by plant parasitic nematodes (*Meloidogyne* spp. and *Pratylenchus* spp.) and fungi (*Fusarium* spp. and *Rhizoctonia* spp.) (Khoa et al 2014; Hoa et al 2016; Hoang et al 2021). These pathogens are well-known as the most economically damaging diseases in coffee-producing countries globally, including Vietnam (Barros et al 2014; Hoa et al 2016; Hoang et al 2021; Machado, Kumar and Fatobene 2023), causing up to 40–50% yield losses (Barbosa et al 2004; Mulatu et al 2023). Soil acidity has been identified as a significant issue in coffee farming systems in Vietnam (Anh and Thuy 2017; Dung et al 2019), with populations of pathogenic fungi and plant parasitic nematodes under crops being 3–5 times higher than background levels (Dung et al 2019). Nematodes and fungi have infected around 36–43% of productive coffee plantations and 79% of replanted coffee farms in the Central Highlands (Khoa et al 2014; Dung et al 2019), resulting in the death of approximately 40% of replanted coffee plantations (Da et al. 2012; Khoa et al 2014). Long-term intensive coffee cultivation with high density (1100 trees ha^{-1}) has created optimal conditions for soil pathogen incidence (Fig. 2) (Arita, Silva and Machado 2020; Machado, Kumar and Fatobene 2023). To control these diseases, farmers used excessive chemical inputs, with their application only increasing in an attempt to maintain high yields in the face of increasing disease pressures (Nysanth et al 2022). Seriously, relying solely on synthetic pesticides can degrade coffee quality, pose health risks, contribute to environmental pollution, and lead to long-term inefficiency (Malta et al. 2003; Mekonen et al. 2014; Silva et al 2017; Duong 2021; Khan et al 2021). Sustainable practices, such as intercropping, biochar and lime application, and agricultural waste applications (e.g., organic fertilizers and mulch), have been identified as potential soil amendments that could help mitigate acidic soil pH, control soilborne diseases, and improve soil fertility and crop yield through complex mechanisms (Beltagi et al 2022; Goldan

Figure 1 An example of a conventional Robusta coffee plantation in Vietnam (monoculture, high density with 1100 trees per hectare, and intensive mineral fertilization and irrigation). Photo credit: Long

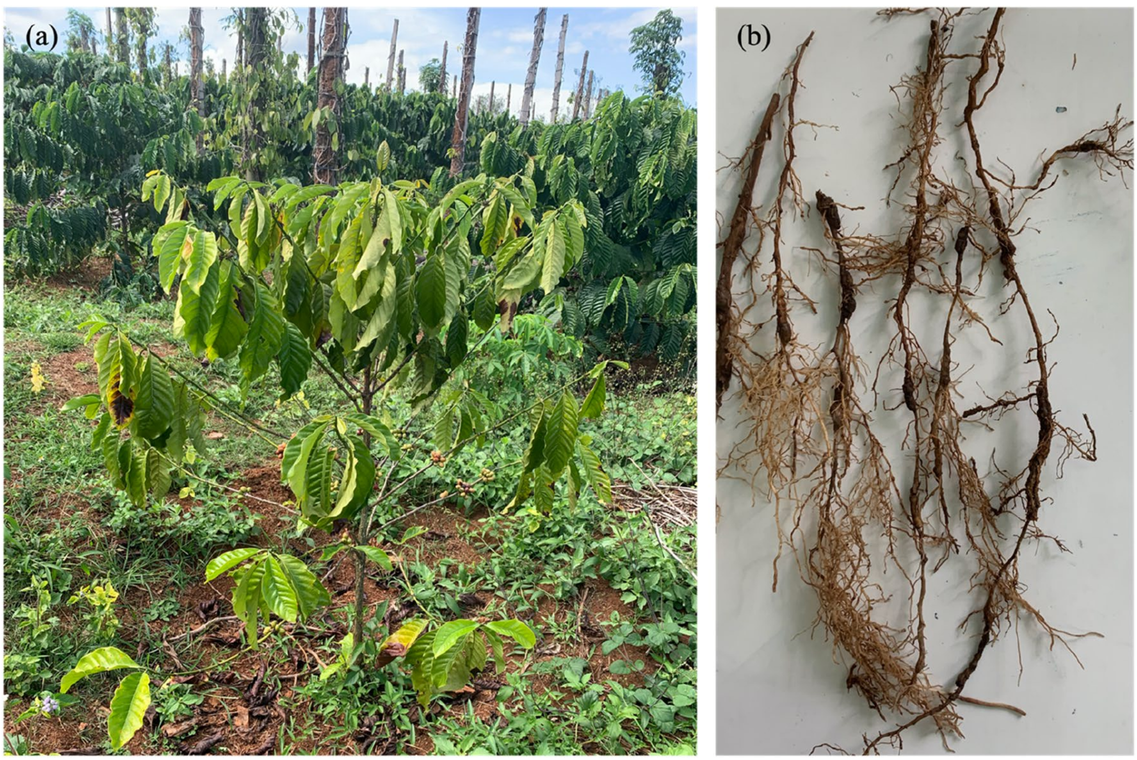


Figure 2 Example of mature Robusta coffee tree infected by plant parasitic nematodes and pathogenic fungi. The specific symptoms are **a** stunting, leaf yellowing and **b** galls on root system. Photo credit: Long

et al 2023; Sánchez et al 2023; Souza et al 2023; Deng et al 2024). However, their effects depend on various factors such as the materials used, application rates, soil types, target species, and agroecological conditions (Li et al. 2018; Rayne and Aula 2020; Poveda et al. 2021) (Fig. 3).

There are currently no studies or reviews that investigate the link between soil acidification and soilborne pests and diseases caused by long-term intensive Robusta coffee cultivation in Vietnam. It is clear that there is a need for more knowledge about potential strategies using sustainable soil practices to remedy the issues. Moreover, knowledge of the mechanisms contributing to soil acidification and the role of soil amendments in protecting coffee from soilborne pests and diseases remains limited. This review paper provides comprehensive insights into the consequences of long-term intensive Robusta coffee cultivation related to soil acidification and the spread of soilborne pathogens, the mechanisms of soil acidification, and the impact of implementing soil amendments on soil acidification and soilborne disease incidence.

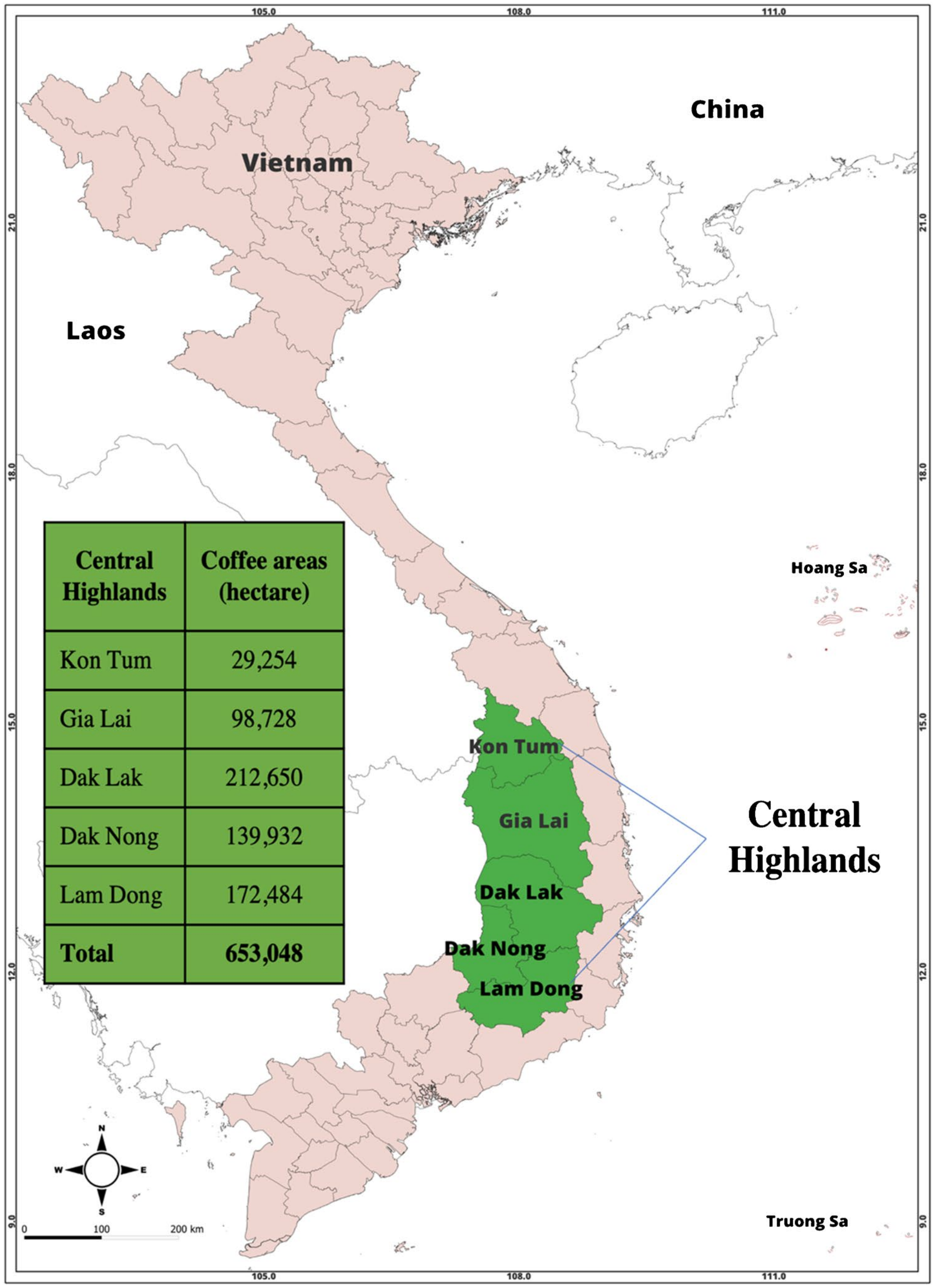


Figure 3 Distribution of coffee cultivated areas in the Central Highlands, Vietnam. The region consists of five provinces, accounting for 90% of the coffee farms (data was retrieved from DCP 2023)

2 Methodology

This review synthesizes findings from studies on soil acidification, soil-borne pathogens, and sustainable amendments in the cultivation of Robusta coffee, particularly in Vietnam's Central Highlands. A systematic search was conducted across the Scopus, Web of Science, and Google Scholar databases to gather comprehensive literature (including peer-reviewed papers, books, and articles) using the keywords "coffee cultivation," "soil acidification," "soil-borne pathogens," and "sustainable soil amendments." The search focused on publications from 1995 to 2024 within the agricultural domain (see Figure 4). A comprehensive search yielded a total of 1679 papers, including 950 from Scopus, 91 from Web of Science, and 638 from Google Scholar. This diverse collection highlights the extensive research available on the topic. Given the limited number of publications specifically addressing the impact of intensive coffee cultivation on soil health indicators in Vietnam, it was necessary to expand the literature search on a global scale. All papers were exported to EndNote 21 (Clarivate Analytics) to identify and remove duplicates and irrelevant topics. Next, we

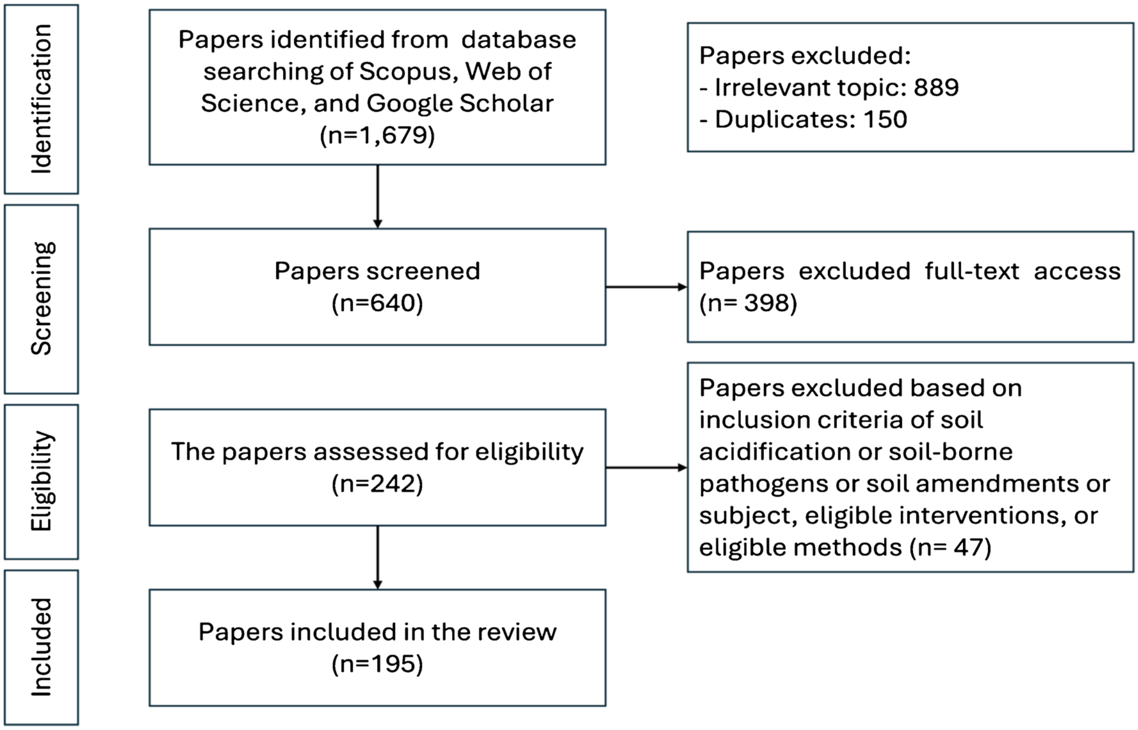


Figure 4 Description of scoping review search method to identify the articles, screen with inclusion criteria, and the number of included studies

screened the titles and abstracts of articles and documents addressing various aspects of intensive coffee plantation, soil acidification, soil-borne disease pressure, and sustainable soil amendments. Ultimately, we selected 195 papers that met our criteria, which included 2 papers published in 1997 and 1999, and 193 articles published between 2000 and 2024. We then carefully reviewed the full texts to identify the study design, findings, and recommendations.

3 Acidification caused by coffee cultivation

Coffee is the key crop in Vietnam that requires the largest application of mineral fertilizers and chemical pesticides. While there is a relationship between coffee yield and fertilizer rates (Castro et al 2012; Byrareddy et al 2019), they are not strongly correlated (Byrareddy et al 2019), and excessive N inputs can also reduce yield (Lesueur et al 2022). Unfortunately, smallholder coffee growers have embraced intensive farming methods and heavily use agrochemicals in attempts to chase high yields (Castro et al 2012; Hong et al. 2017). Vietnam has achieved the highest coffee yield, with an average of 3 t green coffee bean ha^{-1}, compared to other coffee-producing countries (Havemann et al 2015; DCP 2023). The recommended use of mineral fertilizers in coffee cultivation by public extension services varied significantly, depending on soil types, plantation ages, and target yields (MARD 2013). However, mineral fertilizers have been excessively applied up to 50% higher than recommendations (especially N) (Byrareddy et al 2019; Rigal et al 2023).

Soil pH is a critical indicator of soil health, with a broad impact on soil nutrient availability, microbial diversity, and crop production (Lauber et al 2009). One of the main causes of soil acidification in intensified agriculture is the excessive use of mineral N fertilizers (Zhou et al 2013; Zhang et al 2022). Acidification occurs primarily due to the accumulation of H^+ in the soil, resulting from nitrification and urea hydrolysis, which releases protons into the soil (Barak et al 1997). The mechanisms of N application that significantly accelerate soil acidification and increase trace metal toxicity can be explained as follows: (1) N addition directly promotes soil nitrification and hydrolysis (Cai et al 2014; Zhao et al 2020), leading to the indirect stimulation of NH_4^+ or NO_3^- assimilation into root systems (Britto and Kronzucker 2002), resulting in the exudation of H^+ ions; (2) N addition significantly decreases exchangeable Ca^{2+}, Mg^{2+}, and K^+ (Cai et al 2014) while increasing Cd, Mn^{2+}, and Al^{3+} (Tian and Niu 2015; Zhao et al 2020). These processes are summarized in Figure 5.

Zhao et al. (2018) conducted a study on the soil characteristics of coffee plantations with varying lengths of monoculture history and intensive management in Hainan, China. They found that long-term monoculture of intensive coffee farming resulted in a significant decrease in soil pH. There was a difference of about 1.8 pH units between the youngest

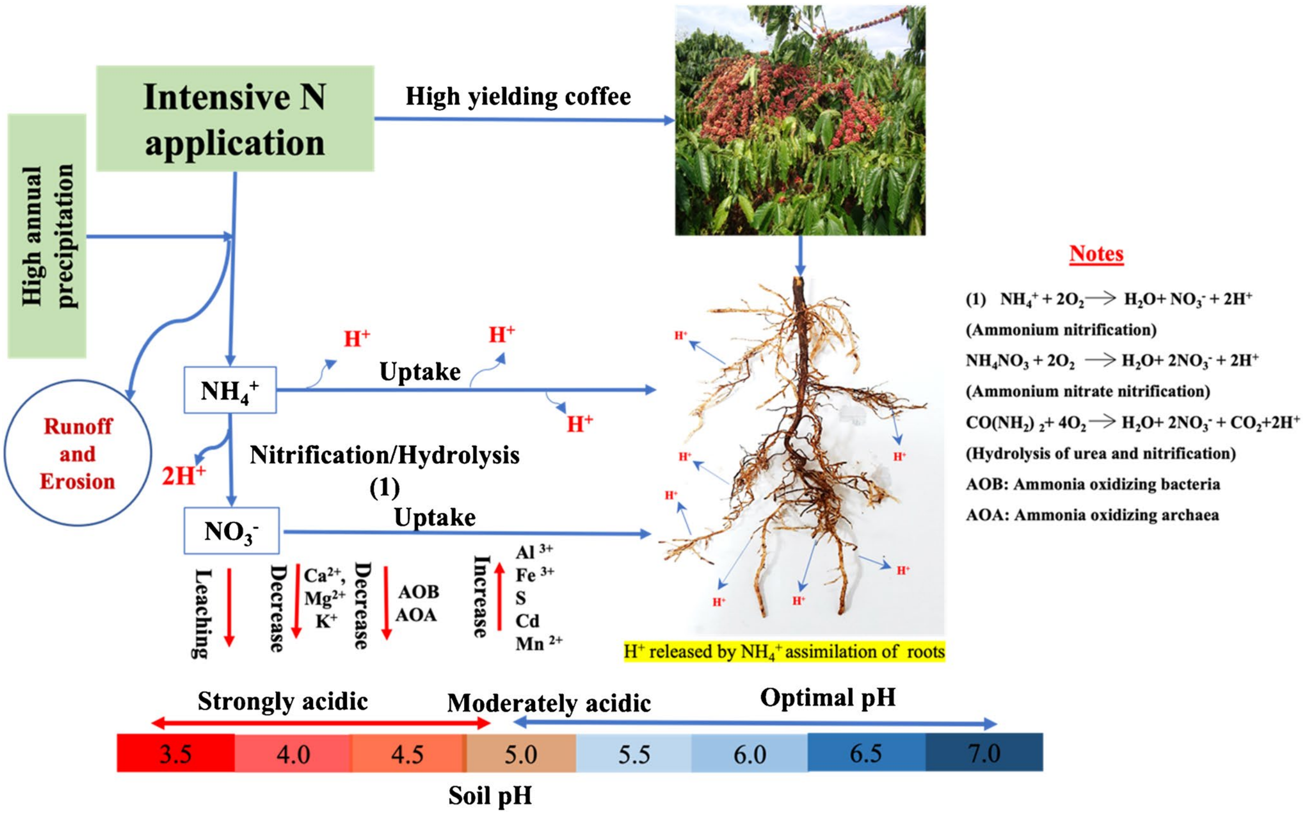


Figure 5 How intensive nitrogen application and high annual precipitation cause soil acidification in coffee plantations in Vietnam

and oldest plantations. In the Central Highlands of Vietnam, coffee plantations currently have strongly acidic soils, with pH levels ranging from 4.06 to 5.64 (Tu and Toan 2015; Ha 2016; Anh and Thuy 2017; Huyen et al 2018; Dung et al 2019). These acidic soil conditions lead to nutrient limitations, such as low phosphorus availability and toxicities from Al and Mn. These conditions are also exacerbated by leaching from the high annual precipitation, ranging from 1800 to 2000 mm in the Central Highlands (Dinh, Aires and Rahn 2022).

4 Effects of soil acidification in coffee plantations

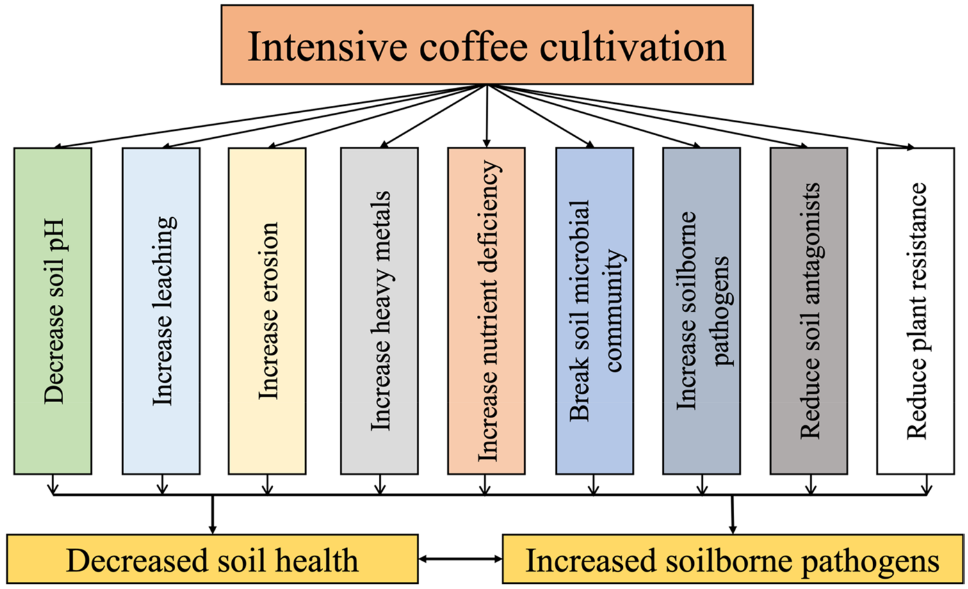
4.1 Physicochemical effects

One of the most harmful effects of soil acidification is an increase in Al and Mn bioavailability, which can be toxic to crops (Rosilawati et al. 2014; Wang et al 2015). When the pH drops below 5.6, the production of H^+ and Al^{3+} occurs much faster (Cai et al 2014). High concentrations of Al^{3+} and Mn^{2+} in acidic soil can lead to deformities and dysfunction of the root system, inhibiting root cell development (Barcelo and Poschenrieder 2002; Kochian et al. 2004) and growth (Zu et al. 2014; Panhwar et al. 2020).

Soil acidification also decreases soil exchangeable base cations, causing nutrient imbalance and deficiency, adversely impacting plant growth (Cai et al 2014; Tian and Niu 2015). Base cations are also known to buffer the soil pH (Tian and Niu 2015; Zhao et al 2020). Acidification promotes the leaching of base cations such as Ca^{2+}, Mg^{2+}, K^+, and Na^+ and allows H^+ and Al^{3+} ions to concentrate in the exchangeable cation pool (White 2006; Neina 2019). Similarly, P is bioavailable at a neutral pH, but only 30% remains bioavailable at a pH below 6. Similar observations are found for available N and K, which decrease by 30% and 50% at pH 5.5 and 5.0, respectively, compared to a neutral pH (Zimdahl 2015).

Several studies have investigated the impact of intensive management on the soil of coffee plantations in Vietnam (Anh and Thuy 2017; Hong 2017; Dung et al 2019). Soil porosity declined by 9–48%; Al and Fe bioavailability increased by 41% and 27% (Ha 2016) and Ca and Mg bioavailability. In addition to the degradation of soil health, plant health is also negatively impacted by soil acidification, as it reduces plant defense (Liao, Li and Yao 2019; Joseph et al 2021; Zhang, Wang and Feng 2021) (Fig. 6).

Figure 6 Summary of the relationships between intensive coffee cultivation, soil health, and soilborne pathogens



4.2 Biological effects

The root microbiome acts as a biological barrier and plays a crucial role in enhancing plant resistance to abiotic and biotic stresses, improving nutrient uptake, protecting plants from pathogen infection, regulating soilborne disease occurrence, and promoting plant growth (Banerjee and Heijden 2023; Wu et al 2023). Soil acidification has been found to decrease the biodiversity of soil organisms. For example, at pH < 4, 70% of important soil biota was lost (Han et al. 2007), and soil fauna community composition at pH 7.0 was significantly higher than at pH 3.5 (Wei et al 2017). Relative abundance and diversity of bacteria at soil pH 8.3 were double compared to soil pH 4.0 (Rousk et al 2010). Moreover, soil enzymatic and microbial activities, along with microbial biomass, are strongly negatively correlated with soil acidification (Zhang et al 2015; Shili et al 2017). Ammonia-oxidizing bacteria and ammonia-oxidizing archaea play a vital role in N cycling and nitrification, and they are adversely impacted by acidic soil pH (Epelde et al 2010; Wang et al 2018b; Zhao et al 2020).

Acidification promotes the growth of pathogens and decreases beneficial microbiomes and plant resistance to disease. This results from the deterioration of soil parameters and reduced available soil nutrients (Fan et al. 2018; Zhang et al. 2022). Mulder et al. (2005) reported a close relationship between nematodes, fungal and bacterial abundance, and soil acidification. Decreased pH directly disrupts the balance of soil microbial communities, shifting from bacterial-dominant to fungal-dominant communities and promoting the growth of soilborne pathogens (Deng et al 2024). Zhang et al (2017) found that bacterial richness and diversity indexes were significantly lower in acidic soils, while the abundance of pathogenic fungi (such as *Cladosporium*, *Pyrenochaeta*, and *Exophiala*) gradually increased (Deng et al 2024). An example of the effects of acidic soil is the 90% decrease in the abundance of *Rhizophagus irregularis*, inhibiting arbuscular mycorrhizal fungi development and formation (Liu et al 2020). Soil pH strongly influences bacteria, particularly beneficial microorganisms, more than fungal abundance (Branco et al. 2022; Coleine et al. 2022; Deng et al. 2024). Zhao et al (2018) demonstrated that long-term monoculture coffee in Hainan, China, with intensive management, decreased soil pH and organic matter content (OM). This resulted in a decline in soil bacteria and fungi abundance over time. Specifically, the relative abundances of bacterial *Proteobacteria*, *Bacteroidetes*, Nitrospira, and fungal Ascomycota phyla decreased. Additionally, acidic soil in coffee plantations was found to promote the growth and reproduction of plant parasitic nematodes, particularly root-knot nematodes (Wang et al. 2009; Nisa et al 2021). The soil acidity indirectly decreased the abundance and diversity of antagonistic microorganisms due to soil nutrient deficiency. Since antagonistic microorganisms rely heavily on soil nutrients, soil pathogens are less reliant on soil nutrients and more reliant on their host plants; thus, the growth inhibition of antagonistic microorganisms and the promotion of pathogens in the soil micro-ecosystems occur (Cortois et al 2016; Shen et al 2018; Zhang et al 2022; Deng et al 2024).

Due to the perennial nature and intensive cultivation of coffee crops, in addition to changes in soil properties, a significant increase in nematode parasitism in crops and nematode density in soils has been observed (Arita, Silva and Machado 2020; Machado, Kumar and Fatobene 2023). Reports have also indicated that *Fusarium* species cause severe damage to coffee production, leading to a significant decrease in coffee yield (Mulatu 2019; López et al 2020; Faifi et al 2022). It is important to note that nematodes and fusarium coexist in infected plantations, making management challenging (Khoa et al 2014; Khan 2023). In Vietnam, approximately 40% of replanted coffee plantations failed due to nematode and fungal infections (Da et al. 2012; Khoa et al. 2012; Dan and Van 2016). Nematodes have been identified as the primary pathogens or predisposing agents, with the independent capability to attack and weaken host plants, leading to modifications that promote fungal and bacterial invasion and increase fungal pathogenicity (Nair 2021; Salgado and Terra 2021; Khan et al 2023). Therefore, managing nematodes could indirectly reduce the threat of *Fusarium* infections in coffee plantations.

5 Potential effects of soil amendments on soil health and soilborne pathogens

Many amendments (e.g., lime, biochar, and agricultural wastes) have been trialed to decrease soil acidification and ameliorate soil acidity. Those materials provide nutrients (Dai et al 2018; Amoah et al 2020; Saliu and Oladoja 2021; Siedt et al 2021), reduce H^+, neutralize acid (Dai et al 2017; Shi et al 2019; Rayne and Aula 2020), and improve soil physicochemical and biological parameters (Kader et al 2017; Azim et al 2018; Shuning et al 2020; Wang et al 2020; Siedt et al 2021). Additionally, soilborne pathogen management by soil amendments resulted from the various mode actions through soil pH increase, modifying soil characteristics, microbial community, and function, especially significantly enhancing the abundance of beneficial biocontrol fungi, promoting the induction of plant defenses, increasing nutrient and space competition, and producing pathogen-inhibiting compounds (Jaiswal et al 2017; Abbott et al 2018; Deng et al 2024). Due to extreme acidification, increasing soil pH is an urgent and mandatory practice to raise soil pH, improve soil health, and retain coffee production. Furthermore, the high demand for "green" coffee products and maintenance of certain yield levels, restoring soil health, and control of soilborne diseases through sustainable practices is a positive strategy.

5.1 Potential effects of biochar amendment

5.1.1 Soil physicochemical effects

The alkalinity of biochar was demonstrated through its calcium carbonate equivalent, which can significantly improve soil pH, affect soil properties, and suppress soilborne pathogens. Increasing the amount of biochar application gradually raises soil pH and improves acidic soil and soil properties due to the alkaline nature and high pH buffering capacity of biochar (Chintala et al 2013b; Dai et al 2017). Since most biochar is alkaline, it directly increases pH and base cations and decreases H^+ and Al^{3+} concentrations in acidic soil, with no positive effect in alkaline soil (Zwieten et al 2010). Carbonates and oxides formed from the pyrolysis process of feedstocks react with H^+ and Al^{3+} in the soil, thereby raising soil pH and reducing the exchangeable acidity (Novak et al 2009; Enders et al 2012). Additionally, the functional groups of biochar (-COO- and -O-) also react with H^+ in the soil (Yuan et al. 2011). The mitigation of soil acidity by biochar addition in coffee cultivation was investigated in greenhouse and field conditions. Soil pH value increased by varying amounts, from 0.03 to 1.17 units, depending on biochar feedstocks, application rate and method, and ecological conditions. The positive effects of biochar on coffee cultivation are summarized in Table 1. Generally, under greenhouse conditions, a 2% biochar application increased pH by 1.1 units, significantly decreasing Al, compared to the control (Herviyanti et al 2020). In field conditions, soil pH was 0.18, 0.23, and 0.37 units higher than the control after two years of adding 4, 8, and 16 t ha^{-1}, respectively (Sánchez et al 2023).

The molecular structure of biochar and the acidic aromatic carbon in biochar are primary factors contributing to soil nutrient improvement and providing agronomic benefits (Zhang, Wang and Feng 2021). These factors promote cation adsorption, raise CEC, improve mycorrhizae and bacteria abundance, enhance the availability of N and P, and reduce leaching and N_2O soil emissions (Atkinson et al. 2010; Güereña et al 2013). For example, coffee husk biochar increased soil porosity (7.5–13.1%), soil moisture (6.6–12.3%), OM (16.9–21.4%), CEC (25.0–30.5%), %N (8.7–12.5%), available P (15.9–17.1%), and K (3.6–3.7%). These changes have promoted plant growth and increased coffee yield by 17.2–24.5 % (An, Cong and Hoa 2023). Furthermore, reactive functional groups on the biochar surface can absorb and detoxify heavy metals (Li et al 2017; Zhao et al 2017), and biochar mitigates climate change by reducing greenhouse gas emissions (Karhu et al 2011). However, it has been reported that biochar application can accumulate heavy metal pollutants such as As, Ni, Cu, and organic pollutants (Jin et al 2016) if care is not taken to screen these out from feedstocks before pyrolysis (Xiang et al 2021). Additionally, many previous studies have reported the positive effects of biochar on soil behavior and plant growth, particularly in acid soils and under controlled conditions (Jones et al 2012; Premalatha, Poorna Bindu, Nivetha et al 2023; Khan et al 2024). However, the impacts observed in controlled environments may differ in field conditions and need further validation (Han et al 2023).

5.1.2 Soil biological effects

The addition of biochar has a positive impact on the microbial community and structure. It increases microbial taxonomic and functional diversity and activities in the rhizosphere due to the increased pH, which provides optimal conditions and habitat (Jaiswal et al 2017; Sun et al 2018). For example, biochar has been shown to increase bacterial diversity by 25% (Kim et al 2007) and to enhance arbuscular mycorrhizal colonization by 10–20% (Solaiman et al 2010). However, there are some drawbacks to using biochar, including a decrease in the abundance of beneficial fungi and an increase in bacterial nitrification (Gundale and Luca 2006; Rondon et al. 2007; Anderson et al. 2011; Nie et al. 2018).

Biochar can help manage soilborne pathogens through various mechanisms. It increases the abundance of beneficial genera, regulates the balance of the soil microbial community and functions, and can suppress soilborne plant diseases, promote plant growth, and enhance biological nitrogen fixation (Jaiswal et al 2017). The introduction of biochar led to a significant increase in the abundance of *Rhizobium*, *Mesorhizobium*, *Brevundimonas*, and *Ochrobactrum* of 2- to 10-fold; *Pseudomonas*, *Paenibacillus*, *Shinella*, and *Bacillus* of 10- to 20-fold; and *Microvirga* of 91-fold compared to the control. Some members of *Pseudomonas, Bacillus*, and *Streptomyces* are known to produce antibiotics, thereby increasing their abundance can help suppress soil pathogens (Jaiswal et al 2017). Additionally, biochar has been found to reduce the relative abundance of soil fungal pathogens (*Ceratobasidium* and *Monosporascus*) by stimulating soil polyphenol oxidase (Ge et al 2023). This reduction in soilborne pathogens is also attributed to promoting nutrient and space competition and the production of pathogen-inhibiting compounds (Joseph et al 2021).

Crucially, changes in soil properties due to biochar characteristics, application rates, and soil types should be considered (Poveda et al 2021). It is important to consider the risks associated with biochar, such as decreased abundance of microorganisms and accumulation of heavy metals. Additionally, the cost of biochar incorporation may be prohibitive for small coffee farmers (Siedt et al 2021). Excessive use of biochar could have negative effects on soil microbial activities, nitrogen levels, and production costs (Gundale and Luca 2006; Rondon et al 2007; Dai et al 2017; Cong et al 2023; Khan et al 2024a, b), indicating the need for further research to verify the benefits of biochar.

Moreover, the modification of nematode populations (Zhang et al 2013; Poveda et al 2021) and the decomposition of biochar (Rahayu and Sari 2017) contribute to the reduction of nematode densities. For example, the population of *Pratylenchus coffeae* with a 4% biochar addition was significantly lower than the control after a three-month experiment (Rahayu and Sari 2017). Similarly, biochar amendment led to a 61.4–73.1% decrease in *Pratylenchus* spp. in coffee roots and 23.6–32.1% in *Fusarium* spp. in the soil compared to the control (An, Cong and Hoa 2023). The increase in soil pH due to biochar application could reduce nematode abundance and inhibit the growth and reproduction of root-knot nematodes (Wang et al. 2009; Nisa et al 2021).

5.2 Potential effects of lime amendment

5.2.1 Soil physicochemical effects

Applying lime to soil increases pH, alters soil chemical and biological properties, and helps control soilborne diseases (Deng et al 2024). Agricultural liming materials are valuable resources that consist of Ca and/or Mg compounds, essential for effectively neutralizing soil acidity and enhancing soil health. When these materials are applied to the soil, carbonate and hydroxide ions neutralize, reduce, and displace hydrogen ions from the soil solution (Mahmud and Chong 2022), raising the soil's pH value. Several studies in greenhouse and field conditions have shown that applying 1.6–4.8 t lime ha^{-1} in coffee cultivation increased soil pH values by 0.4 to 1.3 units (Table 2) (Cyamweshi et al 2014; Dibaba 2021; Parecido et al 2021; Teshale, Kufa and Regassa 2021; Fitria and Soemarno 2022). The addition of lime improves soil physical parameters such as flocculation, aggregates, and porosity by promoting greater particle dispersion and increasing mean aggregate formation (Junior et al 2020). Soil structure improvement results from reduced turbidity, indicating increased aggregate stability (Ulén and Etana 2014; Gunnarsson et al 2022).

Furthermore, lime enhances the mobility and availability of essential plant nutrients through abiotic and biotic processes and immobilizes toxic heavy metals (Li et al 2018; Silva et al 2019). Lime also provides Ca and Mg as nutrients that plants can uptake (Silva et al 2019), promoting soil fertility enhancement. The application of 4.8 t lime ha^{-1} significantly increased N, P, and K from 0.16 to 0.19%, 8.59 to 16.40 ppm, and 0.49 to 0.77 meq 100 g^{-1} soil, respectively (Dibaba 2021). Lime amendment decreases Al^{3+}, increases methane oxidation, and reduces greenhouse gas emissions by inhibiting the activity of methane oxidizers in acidic soils (Kunhikrishnan et al 2016).

5.2.2 Soil biological effects

Soil pH increases, as regulated by adding lime, are key factors that directly affect the presence of soil pathogens and trigger plant defense against diseases (Deng et al 2024). Higher soil pH and nutrient levels promote the diversity of microbial communities and enhance the population of beneficial bacteria (such as *Bradyrhizobium*, *Rhodoplanes*, *Mesorhizobium*, and *Gemmatimonas*), which helps in restoring and balancing soil microbiomes and suppressing soilborne pathogens (Deng et al 2024). Moreover, the abundance of pathogenic fungi (like *Cladosporium*, *Pyrenochaeta*, and

Table 1 Summary of previous investigations of the application of biochar to mitigate soil acidification, improve soil health, and coffee growth

Soil type, location	Experiment type, liming rates, and time	Soil pH effect	Other positive and or/negative effects on soil, plantations, and the environment	References
Basalt soil (pH:4.58) Vietnam	Field trial. Coffee husk biochar rates: 100% NPK (control), 1.0 t biochar + 80% NPK ha^{-1}, 2.0 t biochar + 80% NPK ha^{-1}, 3.0 t biochar + 80% NPK ha^{-1} Trial time: 5 months	Soil pH increased by 1.05–1.17 units compared to the control	Addition of 2–3 t biochar increased soil porosity (7.5–13.1%), soil moisture (6.6–12.3%), OM (16.9–21.4%), CEC (25.0–30.5%), %N (8.7–12.5%), available P (15.9–17.1%), and K (3.6–3.7%) *Pratylenchus* spp. density in roots reduced by 61.5–73.1%, *Fusarium* spp. decreased 23.6–32.1%	An, Cong and Hoa (2023)
Ultisols (pH: 4.17) Indonesia	Greenhouse trial. Young coconut waste biochar and soil were mixed evenly Biochar rates: 0.0% (control), 0.5%, 1.0%, 1.5%, and 2.0% Trial time: 3 months	Soil pH has increased by 1.1 units for the rate of 2% biochar addition compared to the control	2% biochar addition increased available P, organic C, and CEC by 1.70 ppm, 0.99%, and 9.12 cmol[+] kg^{-1} compared to the control. Ca, Mg, and K increased along with the increase in rates of biochar The effect of biochar was not significantly different in the increase in plant growth after 3 months among biochar rates	Herviyanti et al (2020)
Andisol soil. (pH:5.50) Colombia	Field trial. Coffee pulp biochar rates: 0 (control), 4, 8, and 16 t ha^{-1} Trial time: 2 years	Soil pH increased by 0.18–0.37 units according to the increase in biochar rates	Rates of 8 and 16 t ha^{-1} reduced bulk density by 0.82 and 0.83 g cm^{-3}, respectively, and increased aggregation status by 96.5% and 96.84% compared to the control Decreased up to 60% of the exchangeable acidity; increased OM by 0.27% and soil respiration by 50–60%	Sánchez et al (2023)
Basalt soil (pH:4.58) Vietnam	Field trial. Coffee husk biochar was applied to the soil surface. Biochar rates: 100% NPK (control), 0.5 t biochar + 75% NPK ha^{-1}, and 1.0 t biochar + 75% NPK ha^{-1} Trial time: 15 months	Soil pH increased slightly by 0.03 and 0.05 after applying 0.5 and 1.0 t of biochar ha^{-1} compared to the control	Compared to control, soil moisture raised by 5.33% and 7.02%, available P increased by 21.8 and 42.8%, at the rates of 0.5 t and 1.0 t biochar ha^{-1}, respectively CEC rose from 8.92 (control) to 14.83 (0.5 t biochar) and 14.87 meq 100 g^{-1} (1.0 t biochar). OC%, %N, and K_2O were improved	Thanh et al. (2020)
Oxisols (pH: 3.74) China	Laboratory incubation. Soils were mixed with rice straw biochar Biochar rates: 0%, 1%, 2% and 5% (w/w) Trial time: 21 days	Soil pH levels increased to 3.63, 3.84, 3.95, and 4.27 for the 0%, 1%, 2%, and 5% biochar amendments, respectively	The addition of biochar did not affect the net mineralization rates when compared to the control The net nitrification rates increased between the application rates of biochar	Wang et al (2018a, b)

Table 1 (continued)

Soil type, location	Experiment type, liming rates, and time	Soil pH effect	Other positive and or/negative effects on soil, plantations, and the environment	References
The red soil (pH:4.67) China	Laboratory incubation. Soils were mixed with rice husk and wood sawdust biochar Biochar rates: 0, 2% and 5% (w/w) Trial time: 35 days	The pH value slightly increased, even at the highest level of biochar pH increased by 0.73 from 4.75 to 5.48 after 5% of wood sawdust biochar addition	The soil bulk density declined from 1.01 g cm^{-3} to 0.85 and 0.82 g cm^{-3} after 5% rice husk and wood sawdust biochar added, respectively Water-holding capacity increased by 33.5–51.3%. There was a positive correlation between water-holding capacity and biochar level Exchangeable Ca, K and Mg improved, by contrast, the decline in the contents of soil exchangeable acidity and aluminum resulted as the increasing biochar level For 5% of wood sawdust biochar amendment, the exchangeable acidity and aluminum were reduced by 84% and 88%, respectively	Wang and Liu (2018)
Sandy loam (pH:7.1) China	Laboratory incubation. Soil was mixed evenly with woodchip biochar Biochar rates: 0 (control), 50, and 100 g biochar kg^{-1} soil Trial time: 100 days	Soil pH increased by 1.13 and 1.11 units at the rates of 50 and 100 g biochar addition compared to the control, respectively	Biochar addition increased total C, microporosity, water retention, micro-scale shear stress, macro-scale cohesion, and precompression stress of the amended soils	Ajayi and Horn (2017)
Shallow Aridic Ustorthents (pH: 4.78) America	Laboratory incubation. Corn stover biochar and soil were mixed evenly Biochar rates: 0, 20, 40, and 60 g kg^{-1} soil Trial time: 165 days	Soil pH increased by 0.73, 0.99 and 1.36 units at the biochar rates of 20, 40 and 60 g kg^{-1} soil compared to the control, respectively	EC significantly improved from 92.8 to 113, 130 and 240 µS cm^{-1} followed by the biochar rates of 20, 40, and 60 g kg^{-1} soil, respectively. CEC significantly increased from 7.86 to 14.71, 17.33, and 19.04 cmolc kg^{-1} soil, followed by the biochar rates, respectively Exchangeable acidity also considerably declined from 3.54 to 0.24, 0.07, and 0.02 cmolc kg^{-1} soil, followed by the biochar rates	Chintala et al (2013a)
Shallow Aridic Ustorthents (pH: 4.78) America	Laboratory incubation. Switchgrass biochar and soil were mixed evenly Biochar rates: 0, 20, 40 and 60 g kg^{-1} soil Trial time: 165 days	Soil pH increased by 0.49, 0.91 and 0.74 units for biochar rates of 20, 40 and 60 g kg^{-1} soil compared to the control, respectively	EC significantly improved from 92.8 to 110, 140, and 146 µS cm^{-1}, corresponding to the biochar rates of 20, 40, and 60 g soil kg^{-1}, respectively CEC meaningfully increased from 7.86 to 12.44, 14.87, and 17.51 cmolc kg^{-1} soil, followed by the biochar rates, respectively. Exchangeable acidity also considerably reduced from 3.54 to 0.44, 0.07, and 0.01 cmolc kg^{-1} soil, respectively	Chintala et al (2013a)

Table 2 Summary of previous investigations of the application of lime to mitigate soil acidification and improve soil health and coffee growth

Soil type, location	Experiment type, liming rates, and time	Soil pH effect	Other positive and or/negative effects on soil, plantations, and the environment	References
Alfisols (pH:5.6) Indonesia	Glasshouse trial. $CaCO_3$ was mixed evenly with the soil. Lime rates: 0, 2.5 t ha^{-1} Trial time: 8 weeks	Soil pH increased significantly from 5.63 to 6.36 at 10–30 cm depth and from 5.75 to 6.33 at 30–60 cm depth	Lime increased the availability of cations K, Ca, Mg, and Na, whereas it decreased the levels of Al, Fe, and Mn Saturated soil hydraulic conductivity and CEC also significantly improved due to the addition of lime The combination of 2.5 t lime and 20 t compost significantly improved the soil chemical characteristics and saturated soil hydraulic conductivity	Fitria and Soemarno (2022)
Acidic soil (pH: 4.86) Ethiopia	Greenhouse trial. $CaCO_3$ mixed with soil Lime rates: 0, 5, 10, 15, and 20 g 2.5 kg^{-1} soil Time: not provided	Soil pH increased linearly with an increased rate of lime addition 1.13 units significantly raised soil pH at the rate of 20 g lime	Soil exchangeable (Ca^{2+}, K^+, and Mg^{2+}) was positively correlated with rising lime rate. Maximum available P and nutrient uptake were at 20 g lime addition. Exchangeable acidity was dramatically decreased as the rates of lime increased	Teshale, Kufa and Regassa (2021)
Acrisol (pH:4.6) Brazil	Field trial. $CaCO_3$ was applied as a surface band under the canopy Lime rates: 0, 2.1 and 4.2 t ha^{-1} Trial time: 5 years	Soil pH increased by 0.4 and 1.3 units in the 10–20 cm depth after a 5-year experiment compared to the control	Liming efficiently improved soil chemical attributes up to a depth of 10–20 cm but slightly affected the depth of 20–40 cm Lime increased the concentrations of Ca^{2+}, Mg^{2+}, and leaf Zn but reduced the soil Al^{3+} concentration and the coffee leaf Mn concentration At 2.1 and 4.2 t of lime amendment, better plant height and stem diameter were achieved. The average bean yield rose by 42% compared to the control	Parecido et al (2021)
Acrisols (pH:4.72) Ethiopia	Greenhouse trial. $CaCO_3$ was mixed evenly with soil Lime rates: 0 (control). 1.6, 3.2, and 4.8 t ha^{-1} Trial time: not provided	The rate of 1.6, 3.2, and 4.8 t of lime application increased soil pH by 0.6, 0.9, and 1.04 units, respectively, compared to the control	Exchangeable acidity was reduced from 3.3 meq 100 g^{-1} (control) to 0.47 meq 100 g^{-1} (4.8 t lime ha^{-1}) Total N, available P, and exchangeable K significantly improved as rates of lime addition increased, from 0.16%, 8.59 ppm and 0.49 meq 100 g^{-1} (control) to 0.19%, 16.40 ppm and 0.77 meq 100 g^{-1} (4.8 t lime ha^{-1}), respectively Total dry matter expressionally rose by 14.7–61.8% with increasing rates The application of 3.2 t lime ha^{-1} in combination with 10 t coffee husk compost ha^{-1} obtained high dry matter yield and nutrient uptake	Dibaba (2021)

Table 2 (continued)

Soil type, location	Experiment type, liming rates, and time	Soil pH effect	Other positive and or/negative effects on soil, plantations, and the environment	References
Acidic soil (pH:4.9) America	Laboratory incubation. $CaCO_3$ was thoroughly mixed with the soil. Lime rates: 0, 4.4, 8.8 and 17.6 t ha^{-1} Trial time: 149 days	Soil pH (0–20 cm) increased by 1.0, 1.7, and 2.8 units for the addition of 4.4, 8.8, and 17.6 t lime compared to untreated lime	Organic matter was 7.5–12.5-fold higher in limed than in non-limed soil. Soil nitrate increased over time The respiration rate was higher in limed soil than in non-limed soils Microbial biomass-C at rates of 4.4, 8.8, and 17.6 t lime ha^{-1} were 3.3, 4.4, and 7.2 times higher than the control, respectively	Fuentes et al (2006)
Oxisols (pH: 3.74) China	Laboratory incubation. Soil was mixed with CaO Lime rates: 0% (control), 0.10%, 0.25%, and 0.35% Trial time: 21 days	The soil pH increased to 3.63, 4.04, 4.91, and 6.40, respectively, corresponding to 0%, 0.10%, 0.25%, and 0.35% lime application	Lime addition significantly increased net mineralization rates. The highest figure was at the lime rate of 0.35% The net nitrification rate significantly decreased as the lime addition increased	Wang et al (2018a)

Exophiala) gradually decreases with increasing pH (Deng et al 2024). However, limited reports on managing soilborne pests and diseases through lime amendment in coffee production exist. Additionally, the effects of lime amendment vary and largely depend on the rates and properties of liming materials (Álvarez et al. 2009; Li et al 2018), as well as the initial soil physiochemical characteristics (Bolan et al. 2003). Excessive application of lime did not significantly increase soil pH, however, it led to higher production costs, Ca toxicity (Yan et al 2021; Norberg and Aronsson 2022), soil eutrophication, and damage to soil microbial communities, which in turn exacerbated soilborne diseases (Deng et al 2024). Further research is needed to understand the potential impact of lime amendment on soil health and its ability to suppress soilborne plant diseases in coffee crops in acidic soils (Fig. 7).

5.3 Potential effects of organic fertilizer amendment by plant and animal residues

5.3.1 Soil physicochemical effects

Organic fertilizers are derived from plant and animal sources, such as plant residues and animal wastes (Michael 2021; Badu and Abigail 2022). They offer several benefits, including improving soil physiochemical properties and water retention capacity, reducing erosion, promoting beneficial microorganisms, suppressing plant pathogens, and decreasing reliance on mineral fertilizers (Abbott et al. 2018; Goldan et al. 2023). Organic wastes can also alleviate soil acidification (Citak and Sonmez 2011; Chen et al 2022). For example, applying manure compost to acidic coffee plantation soils increased soil pH by 0.5 units after a three-year trial (Dzung et al. 2013). Organic amendments release organic compounds into the soil, reducing leaching and adsorbing acid cations, resulting in decreased acid availability and retained acid cations (Michael 2021). Additionally, organic fertilizers contain organic anions, bicarbonates, and base cations that enrich in alkaline cations, promoting buffer and neutralizing H^+ ions (Butterly et al. 2013; Abbott et al 2018). However, organic amendments can also decrease soil pH by stimulating ammonium nitrification during the mineralization of organic N and increasing cation replacement H^+ in the exchange sites (Wang et al 2013; Xiao et al 2014; Arafat et al 2020; Lúcio et al 2020).

Organic amendment effectively increases organic matter (OM) from biomass waste (Adugna 2016). This process reduces bulk density and enhances the soil's capacity to hold water and nutrients. It also improves the buffer capacity, microbial activity, nutrient mineralization rates, and soil texture (Brown and Cotton 2011; Badu and Abigail 2022). For instance, adding compost decreased soil erosion

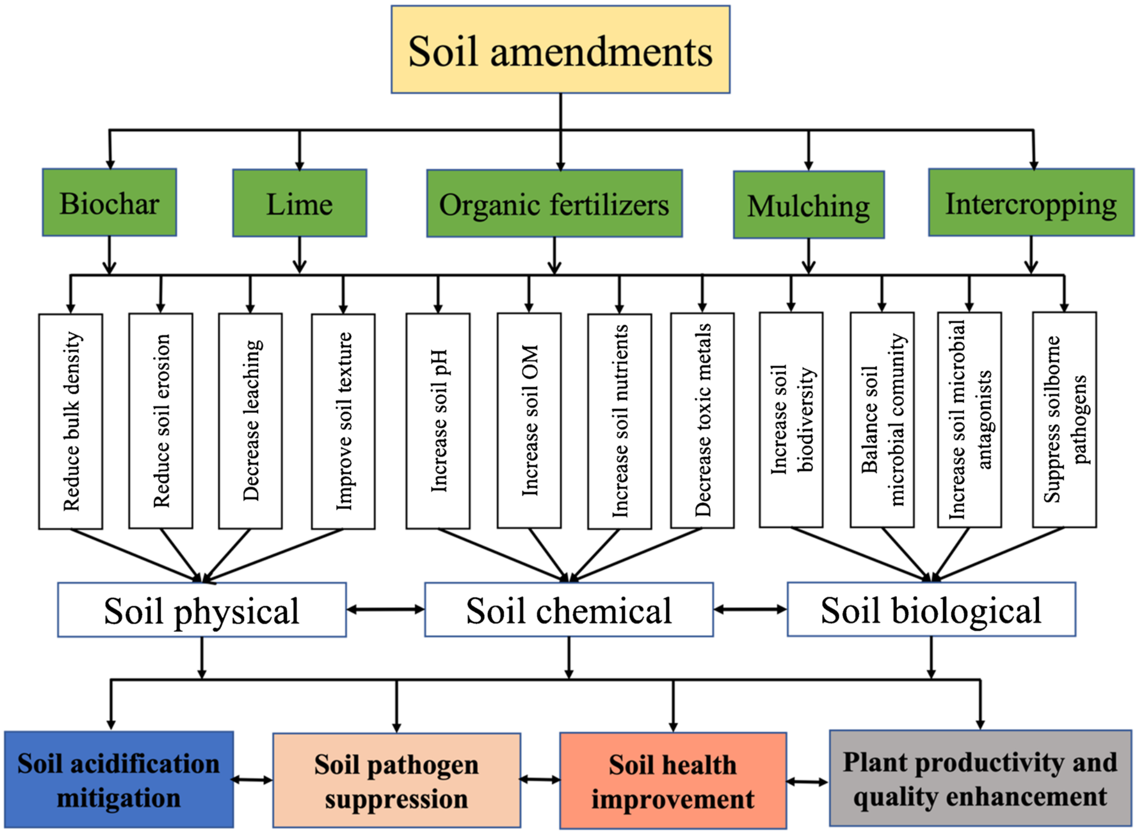


Figure 7 Beneficial effects of some soil amendments on soil properties and soilborne diseases of coffee plantations

by 67%, runoff by 60%, and bulk density by 8%, but it increased OM by 21% compared to the control (Strauss 2003). Organic amendments also provide essential nutrients through the decomposition process, serving as an organic multi-nutrient fertilizer supply to the plant and improving soil quality and productivity (Dzung et al. 2013; Lúcio et al 2020).

5.3.2 Soil biological effects

Additionally, organic amendments stimulate soil biodiversity and suppress disease by reducing the population of soil pathogens, increasing the presence of soil microbial antagonists, and releasing chemical compounds (Abbott et al 2018). Soil fungal and bacterial diversity is improved due to these amendments' provision of food for microorganisms (Brown and Cotton 2011; Rayne and Aula 2020). For example, adding compost in coffee plantations improved soil urease and phosphatase activities by around 96% and 30%, respectively. It also enriched the abundance of bacteria, fungi, and actinomycetes by 62.15%, 46.21%, and 68.42%, respectively (Jiang et al 2023).

To date, there have been limited reviews of the effects of organic fertilizers on the suppression of soilborne pathogens in coffee cultivation. The effects of organic fertilizers on soil properties vary depending on the types of materials, rate of addition, agricultural practices, soil type, and ecological conditions (Citak and Sonmez 2011; Rayne and Aula 2020). Moreover, organic fertilizers made from plant and animal substances can contain pathogens that pose risks to humans and plants (Chen 2006), and large amounts of organic fertilizer are required to increase soil pH and other soil health indicators, which may not be readily available to smallholder coffee farmers and can pose a threat to surface and groundwater pollution (Bhatt, Labanya and Joshi 2019; Goldan et al 2023). The drawbacks of organic amendments also include the acceleration of acidification and the accumulation of heavy metals. Therefore, the potential effects of agricultural organic amendments on acidic soil in coffee plantations should be further investigated.

5.4 Potential effects of organic mulching by plant residues

5.4.1 Soil physicochemical effects

Using organic mulch materials such as plant residues and agricultural wastes can potentially help alleviate soil acidification

(Iqbal et al. 2020; Beltagi et al. 2022). (2019) reported that mulches in coffee farming systems significantly raised soil pH by 0.56 and 0.52 units compared to the control. The decomposition of mulching materials enriched exchangeable base cations and soil organic carbon, which can neutralize and absorb soil exchangeable acidity, thus leading to an increase in soil pH (Li and Johnson 2016; Awopegba, Oladele and Awodun 2017). However, some authors have found negative influences of organic mulches on soil pH (Bekeko 2014; San et al 2021; Beltagi et al 2022) due to increased organic and carbonic acids produced by crop residue decomposition (Bekeko 2014; Arafat et al 2020), and the release of H^+ from the process of mineralization of organic N (Dai et al 2017).

In addition, mulching mitigates soil erosion, reduces water evaporation, improves soil moisture retention, regulates soil temperatures, enhances available nutrients and plant absorption, supports soil biological activities, and suppresses weeds, thereby improving soil health (Ngosong, Okolle and Tening 2019; San et al 2021). Mulches also control fertilizer leaching, enrich soil nutrient availability and soil organic matter content, reduce soil Al^{3+} concentration (Nzeyimana et al 2019; Beltagi et al 2022), and improve soil physiochemical and biological parameters (Albiach et al 2000; Thy and Buntha 2005). After three years of mulching with *Leucaena* variety KX2 trees, total soil OM and N increased by 2.90 and 1.42 t ha^{-1}, respectively (Youkhana and Idol 2015). Soil surfaces covered by organic mulches lead to soil moisture conservation and regulation of soil temperature (colder in summer or warmer in winter) by managing surface evaporation and reducing soil temperature variation (Iqbal et al 2020). These changes are primary factors in coordinating soil microbial community structure and function and enzyme activities (Brockett et al. 2012; Onwuka 2018; Tan et al. 2018).

5.4.2 Soil biological effects

The use of biomass mulches for planting can suppress pests and diseases and rejuvenate soils through different mechanisms (Ngosong, Okolle and Tening 2019). Plant residues provide favorable conditions for anti-pathogenic species (Mochiah and Baidoo 2012), produce chemicals (Ngosong, Okolle and Tening 2019; Iqbal et al 2020), and enhance soil microbial diversity. Coffee pericarp mulch significantly improved bacteria diversity (2.79%) and richness (7.75%), as well as the abundance of *Proteus* (22.35%) and *Chlamydomonas* (80.04%), compared to the control (Zhao et al 2023). Likewise, *Mucuna* sp. mulch promoted antimicrobial activities against bacterial and fungal species such as *Fusarium sporum*, *Rhizoctonia solani*, and *Pseudomonas syringae* (Rayavarapu and Kaladhar 2011). Tomato root galls caused by *Meloidogyne incognita* were reduced by maple leaf mulch due to soil temperature increase (Petrikovszki et al 2016). Mulch materials reduce irrigation water, which carries and spreads disease spores, and support the nutrition of soil-beneficial organisms that compete with pathogens (Iqbal et al 2020). Furthermore, mulches also provide and improve soil nutrients so that plants become more vigorous and can tolerate pathogens (Ngosong, Okolle and Tening 2019).

The impact of different mulching materials on soil health and disease management varies greatly depending on the type of crop, the materials used for mulching, and the specific agricultural conditions (Iqbal et al. 2020; Zhao et al. 2023). The use of mulches can lead to increased labor costs and investment, and the availability of mulch materials may be a challenge for farmers, particularly for smallholder coffee growers (Ngosong, Okolle and Tening 2019). Certain mulching materials can create conditions that promote disease occurrence (Iqbal et al 2020). Excessive mulch application can result in very high soil moisture and N levels, which can limit oxygen supply to the root systems and create favorable conditions for pathogen growth, ultimately harming plant health (Ngosong, Okolle and Tening 2019; Beltagi et al 2022). Therefore, when amending mulch in acidic coffee plantations, both the positive and negative effects should be taken into consideration.

5.5 Potential effects of intercropping and agroforest systems

Intercropping is an effective method for improving soil pH and nutrients, controlling soil diseases, and enhancing the functionality of soil microbes (Vukicevich et al 2016; Reyes et al. 2019). Rigal et al. (2020) discovered that shaded coffee cultivation increased soil pH by 0.5 units and resulted in higher OM, N, and Ca soil contents and a greater abundance of soil microbial communities compared to open coffee cultivation. Similarly, intercropping coffee with papaya improves soil pH and physiochemical characteristics and reduces Al and H+ levels compared to full-sun coffee (Souza, Carlette Thiengo, Silva et al.). The decomposition of plant residues on the soil surface releases water-soluble organic anions that absorb H^+ (Pavan et al 1999). Intercropping practices that enhance OM, microbial biomass, enzyme activities, and nutrients can help suppress disease infections (Medeiros et al 2019). For example, intercropping coffee with buckwheat and Sunn hemp leads to higher parasitism and predation of pests than in monoculture (Rosado et al 2021). Similarly, *crotalaria* species used as intercrops can potentially suppress plant parasitic nematodes and improve soil fertility (Wang, Sipes and Schmitt 2002; László 2010).

On the other hand, some studies have reported no significant differences in soil physical attributes between agroforestry coffee farming systems and conventional cultivation (Carmo et al 2014; Jácome et al 2020). Intercropping can also lead to an increase in the nematode population due to the presence of nematode hosts (Mazzafera et al. 2004). In light of these results, intercropping shows promise as an approach for restoring soil quality and promoting more sustainable practices in intensive coffee production. However, it is important to carefully consider the suitable model of the intercropping system and the choice of crops to intercrop with coffee due to some drawbacks.

6 Conclusion and future perspectives

The intensification of coffee production in Vietnam has brought significant socioeconomic benefits to the country, improving the livelihoods and income of Central Highland farmers. While high yields have historically been achieved through intensive agricultural practices, these practices have led to serious consequences, such as soil acidification and the spread of soilborne pests and diseases, that now heavily reduce coffee yields. Our review found that acidification is a serious issue in Robusta coffee cultivation in Vietnam that is caused by excessive N fertilization. The links between intensive cultivation, acidification, and soilborne pathogens were clearly identified. A low soil pH significantly adversely affects soil physicochemical indicators and promotes the growth of soilborne pathogens. Additionally, the potential effects of soil amendments on mitigating soil acidification, improving soil fertility, and controlling soil diseases were investigated.

However, the effects of various amendments on soil acidification and pathogens can vary significantly due to factors such as the materials used, application rates, soil properties, agricultural practices, and ecological conditions. Several drawbacks include limited resource availability, time-consuming processes, soil acidification, heavy metal accumulation, and environmental risks. Additionally, significant volumes of soil amendments are needed to enhance soil health, which may be economically unfeasible for smallholder coffee farmers and may have other negative effects. Finally, most research on the application of agricultural wastes and products has been conducted outside Vietnam, often in locations with specific but limited soil characteristics, climate conditions, and agronomic practices.

Implementing sustainable coffee farming systems is essential for producing high-quality green products, creating a safe environment, and meeting global market demands. Therefore, agricultural soil amendments are urgently needed to address soil acidification, improve soil health, and suppress soilborne pathogens. This will ultimately reduce the reliance on chemicals and lower production costs for smallholder coffee growers. Disease management through soil amendments modifies soil characteristics, which can be a barrier compared to immediate chemical treatments. However, various chemicals are being prohibited and restricted, resulting from their toxicity to human and animal health, environmental risks, soil pollution, decreased product quality, increased production, and inefficiency after long-term use. Ultimately, this research gap underscores the need for future studies to focus on the effects of acidification on plant health and pathogen growth, as well as on optimizing the use of biochar, lime, and organic amendments to address these challenges and promote sustainability.

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