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Effectiveness of Pruning and Fertilization in Maintaining Soil Fertility and Nutrient Cycling in Coffee Agroforestry Systems: A Systematic Literature Review

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Abstract
Indonesia's relatively low coffee productivity compared to other producing countries indicates serious problems in agroforestry management, particularly soil fertility degradation and nutrient imbalance. Suboptimal pruning and fertilization exacerbate these conditions, necessitating a systematic study to understand their effectiveness. This study aims to evaluate the role of pruning and fertilization in maintaining soil fertility, nutrient balance, and their relationship to coffee productivity. This study used a Systematic Literature Review (SLR) design based on PRISMA 2020 with the PICO framework. It searched literature from Scopus and Web of Science for the period 2015–2025, screened through inclusion-exclusion criteria, assessed quality using the Mixed Methods Appraisal Tool (MMAT 2018), and analyzed data using thematic analysis in NVivo 14. Of the 201 initial articles, 28 met the criteria and were further analyzed. The results indicate that pruning increases organic inputs, improves soil structure, and nutrient cycling efficiency, while fertilization maintains the availability of essential nutrients. The integration of the two resulted in a positive nutrient balance, significantly increasing microbial biomass, soil respiration, and coffee productivity. Literature trends indicate a shift in focus from basic ecological studies to practical strategies for sustainable management. This study concludes that the integration of pruning and fertilization is a key strategy in coffee agroforestry, although further research needs to consider socio-economic dimensions and adaptation to extreme climates to produce more applicable recommendations for sustainable coffee agroforestry.

INTRODUCTION

Coffee is one of the most widely consumed agricultural commodities in the world. According to FAOSTAT (2022), Brazil, Vietnam, Colombia, and Indonesia account for more than 63% of global coffee production, with a total production of 10.8 million tonnes per year. Indonesia ranks fourth among the world's largest coffee producers with an average production of 725,680 tonnes, but its productivity is relatively low compared to other producing countries, at only 811 kg/ha in 2020 (BPS, 2020). Although Indonesia ranks second after Brazil in terms of coffee acreage, the gap between harvest area and productivity indicates serious problems in coffee cultivation management. The downward trend in Indonesian coffee production projected by BPS (2020) until 2026 further reinforces the urgency of improving land management systems. The phenomena of soil fertility degradation, nutrient imbalance, and suboptimal pruning practices are major challenges in Indonesia's coffee agroforestry system.

The problem of low coffee productivity not only affects yields, but also has broader implications for the socio-economic sustainability of farmers and the environment. An imbalance in the nutrient balance due to the removal of harvests without replenishing nutrients through fertilisation can significantly reduce soil fertility (Malavolta, 1990; Schnug et al., 1996). This condition results in a decline in soil quality in terms of chemical, physical and biological aspects, thereby reducing the soil's capacity to support plant growth (Sumarni et al., 2010). The impact is not only on productivity, but also has the potential to cause ecosystem vulnerability, such as increased erosion, reduced carbon reserves, and reduced biodiversity (Supriadi & Dibyo, 2015). Therefore, proper pruning and fertilisation practices in coffee agroforestry systems are urgently needed as a solution to improve soil fertility and maintain nutrient balance, while also addressing environmental sustainability demands.

A number of studies have attempted to answer this question. Cahyono et al. (2020) found that pruning in coffee-pine agroforestry can increase coffee productivity while improving the microclimate. Sinaga and Setyono (2020) showed that higher light intensity on coffee plants due to pruning is positively related to production yields. Meanwhile, studies by Putri et al. (2018) and Thamrin (2014) confirmed that fertilisation, both organic and inorganic, contributes significantly to increased coffee yields, although its effectiveness varies depending on the dose and type of fertiliser. On the other hand, Tinoco-Jaramillo et al. (2024) report that coffee agroforestry systems with specific fertilisation management not only increase nutrient contribution but also play an important role in carbon sequestration. However, previous studies tend to separate the study of pruning and fertilisation without comprehensively evaluating the relationship between nutrient balance, soil fertility, and coffee productivity in an agroforestry management system. This is the research gap that this study attempts to fill, namely by simultaneously testing the effectiveness of pruning and fertilisation in maintaining soil fertility and nutrient balance, while also evaluating their impact on coffee productivity.

This study aims to analyse the effectiveness of pruning and fertilisation in coffee agroforestry systems in improving soil fertility, evaluating nutrient balance, and examining the relationship between nutrient balance and soil fertility on coffee productivity. The implications of this study are the formulation of more appropriate and sustainable coffee agroforestry management recommendations that can support productivity while maintaining soil quality. The importance of this study lies not only in its contribution to increasing coffee yields, but also in its role in supporting food security, farmer welfare, and natural resource conservation through environmentally friendly agroforestry practices.

RESEARCH METHODOLOG

This research methodology uses a Systematic Literature Review (SLR) design that aims to synthesize empirical evidence on the effectiveness of pruning and fertilization in coffee agroforestry systems on soil fertility, nutrient balance, and their implications for coffee productivity. SLR was chosen because it is able to present integrated and tested findings from various research contexts, thereby reducing researcher subjectivity bias and increasing the reliability of conclusions (Snyder, 2019). The SLR process was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, which provide a systematic framework for identifying, selecting, and reporting literature (Page et al., 2021).

The PICO (Population, Intervention, Comparison, Outcome) framework was used to guide the formulation of research questions and the focus of the literature review. The PICO in this study is shown in Table 1.

Table 1. PICO Framework

Component	Description
Population (P)	Coffee agroforestry systems (Coffea arabica and Coffea canephora)
Intervention (I)	Pruning and fertilisation (organic, inorganic, or combination)
Comparison (C)	Practices without pruning or minimal/conventional fertilisation
Outcome (O)	Soil fertility (physical, chemical, biological), nutrient balance, and coffee productivity

The literature search strategy was conducted on reputable international databases, namely Scopus and Web of Science. The publication range searched was the last ten years (2015–2025) to ensure the relevance and novelty of the findings. Keywords were compiled using Boolean operators and truncation to broaden the scope of the search, for example: *'coffee' AND ('agroforestry' OR 'forest farming') AND ('pruning' OR 'trimming' OR "fertilisation" OR 'enrichment')*. The article selection process was conducted based on explicitly defined inclusion and exclusion criteria (Table 2).

Table 2. Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Empirical articles focusing on coffee agroforestry	Articles in the form of reviews, editorials, or opinions
Analysing pruning, fertilisation, or both	Non-coffee research (e.g. cocoa or tea agroforestry)
Measuring impacts on soil fertility, nutrient balance, or productivity	Articles not available in English or Indonesian
Published in the last 10 years (2015–2025)	Articles without full access or only available as abstracts

Identification, selection, and extraction of articles were carried out following the PRISMA 2020 flow, which consists of four stages: identification, screening, eligibility, and inclusion (Page et al., 2021). Each stage is accompanied by a PRISMA diagram to visualise the number of articles at each screening step.

To assess the quality of articles that passed the selection, the 2018 version of the Mixed Methods Appraisal Tool (MMAT) was used, which allows for the evaluation of quantitative, qualitative, and mixed articles (Hong et al., 2018). Articles were assessed based on five main criteria, including clarity of research objectives, design appropriateness, data relevance, analysis validity, and consistency of results. Articles with low scores (<40%) were excluded from the final synthesis to maintain the validity of the findings.

Data from selected articles were extracted using an extraction table containing key information, such as author, year, research location, type of intervention (pruning/fertilisation), analysis method, and key findings related to soil fertility, nutrient balance, and coffee productivity. Data analysis was conducted using a qualitative thematic approach in NVivo 14. This process included open coding, code grouping, and the development of main themes relevant to the research questions. Thematic analysis enabled the identification of patterns, contradictions, and relationships among variables, resulting in a more comprehensive synthesis.

The division of labor among the three researchers was carried out to ensure transparency and minimize bias. The first researcher was responsible for literature searches and initial screening based on titles and abstracts. The second researcher conducted a full eligibility check on articles that passed the initial stage and assessed their quality using MMAT. The third researcher coordinated the data extraction process, thematic analysis in NVivo 14, and compiled the SLR report. Any differences of opinion were resolved through joint discussion until a consensus was reached.

Through this rigorous methodological approach, SLR is expected to provide a comprehensive understanding of the role of pruning and fertilization in coffee agroforestry systems on soil fertility, nutrient balance, and coffee productivity. The results of this study are expected to strengthen the scientific basis for sustainable agroforestry management recommendations and to make a significant contribution to the development of agronomy and agricultural policy.

RESULTS AND DISCUSSION

The PRISMA flow diagram illustrates the systematic study selection process from identification to inclusion. Of the total 201 initial records obtained through Scopus (104) and WoS (97), 62 were removed due to duplication, leaving 139 for selection. During the screening stage, 93 articles were excluded because they did not meet the criteria, such as being published before 2015, not being in English, being reviews, proceedings, books/book chapters, or being irrelevant based on the title and abstract. Next, 46 full reports were requested, but 4 were inaccessible, leaving 42 reports to be evaluated for eligibility. From the full evaluation, 14 articles were excluded because they did not match the research question, leaving 28 studies that were ultimately included in the review. The arrows to the right in the diagram show each stage of exclusion that narrowed the number of articles, so that only the most relevant studies that met the criteria were included in the analysis.

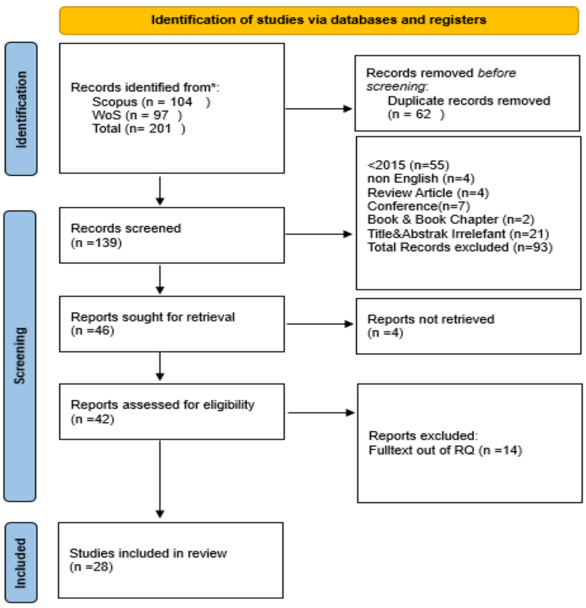

Figure 1

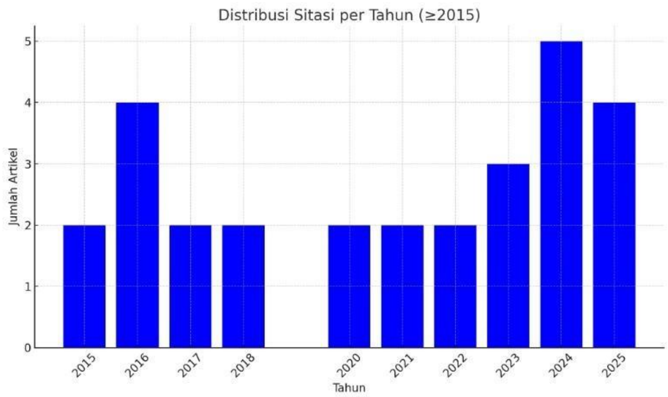

Figure 2. Citation distribution per year

The graph of citation distribution per year shows a significant increase in the number of articles from 2015 to 2025. In the early period, the number of citations was relatively low, with only two articles in 2015 and four articles in 2016. Subsequently, the trend was relatively stable with 2–3 articles per year in the range of 2017–2023. However, there was a sharp increase in 2024 with 5 articles and a peak in 2025 with 4 additional articles, reflecting the increasing relevance and attention to research on the topics of coffee agroforestry, fertilisation, and soil fertility management in recent years. This pattern confirms that scientific studies related to these topics have intensified in the most recent period, in line with the increasing need for sustainable agricultural systems.

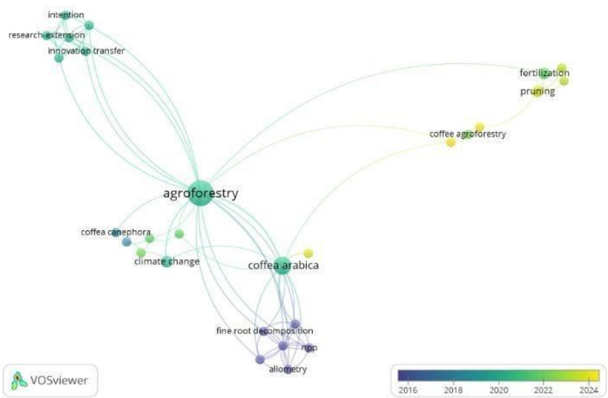

Figure 3. VOSviewer visualisation

This VOSviewer visualisation overlay shows the evolution of coffee agroforestry research themes based on publication year. The blue-purple colour represents older topics (around 2016–2018) such as allometry, fine root decomposition, and npp, which focus on basic biophysical and ecological aspects. Subsequently, around 2019–2021, issues of climate change and Coffea canephora emerged, signalling a shift in attention towards the adaptation of agroforestry systems to climate change. In the more recent period (2021– 2023, coloured green), research topics expanded to include innovation transfer, research- extension, and intention, emphasising social dimensions, technology adoption, and knowledge transfer. The latest trend (2023–2024, shown in yellow) is concentrated on specific management practices such as coffee agroforestry, pruning, and fertilisation, signalling a more applied and technical orientation of research. This pattern illustrates that coffee agroforestry research has evolved from basic ecological studies to climate adaptation issues, then transformed into the integration of social innovation, and finally focused on practical cultivation strategies that support sustainable production.

The VOSviewer analysis shows that coffee agroforestry research has shifted from early ecological studies (e.g., allometry and root processes), to climate change adaptation, then to social and innovation aspects, and most recently to practical management strategies.This progression highlights a growing emphasis on applied solutions, where pruning and fertilization emerge as key practices because they directly address core challenges such as soil fertility decline, nutrient imbalance, and productivity improvement. Therefore, focusing on these practices is important as they represent actionable strategies to enhance sustainable coffee production.

The Effectiveness of Pruning and Fertilisation Integration in Maintaining Soil Fertility in Coffee Agroforestry Systems

Pruning and fertilisation in coffee agroforestry systems have been proven effective in maintaining soil fertility because they complement each other in the nutrient cycle. Pruning shade trees increases the input of organic matter into the soil through litter, which serves as a major source of nutrients and improves the physical and biological properties of the soil (Wibawa et al., 2010, in Rigal et al., 2020). Decomposed litter not only increases nutrient reserves but also reduces nutrient competition between coffee plants and shade trees. On the other hand, proper fertilisation, both organic and inorganic, increases the availability of essential nutrients such as nitrogen, phosphorus, and potassium, which are especially needed during the fruit filling phase (Kairu et al., 2012, in Rigal et al., 2020). The combination of pruning and fertilisation maintains a balanced nutrient balance, thereby reducing the risk of nutrient loss due to leaching or deficit (Rigal et al., 2018, in Rigal et al., 2020). A positive nutrient balance contributes to increased soil fertility and supports sustainable coffee productivity (Vaast et al., 2006, in Rigal et al., 2020). Conversely, nutrient deficits cause a decline in soil fertility, which results in reduced coffee yields, making integrated pruning and fertilisation management a key strategy for sustainable agroforestry systems (Bote & Struik, 2011, in Rigal et al., 2020).

Analysis of the integration of pruning and fertilisation in coffee agroforestry systems shows that these practices are not merely cultivation measures, but part of an ecosystem management strategy that supports sustainability. Regular pruning of shade trees increases the input of organic matter that enriches soil fertility, while reducing nutrient competition between plants (Wibawa et al., 2010, in Rigal et al., 2020). The decomposition process of litter produces essential nutrients that synergise with fertilisation, thereby increasing nutrient use efficiency. Timely fertilisation according to the needs of coffee plants increases the availability of nitrogen, phosphorus, and potassium, especially during the critical fruit filling phase (Kairu et al., 2012, in Rigal et al., 2020). This analysis emphasises the importance of understanding the ecological interactions between shade trees, litter, and fertilisation in maintaining a positive nutrient balance. Without the right combination, agroforestry systems have the potential to experience nutrient imbalances that impact soil fertility and coffee productivity (Bote & Struik, 2011, in Rigal et al., 2020). Thus, integrated management practices can be considered the key to maintaining the sustainability of coffee agroforestry.

Findings from various studies confirm that the integration of pruning and fertilisation significantly contributes to increased soil fertility in coffee agroforestry systems. Pruning has been shown to increase the supply of organic litter that supports the natural nutrient cycle, while fertilisation increases the availability of nutrients needed by coffee plants to grow optimally (Rigal et al., 2018, in Rigal et al., 2020). This practice creates a positive nutrient balance that has a direct implication on increasing coffee productivity (Vaast et al., 2006, in Rigal et al., 2020). Findings also show that the combination of the two is more effective than separate application, as it can reduce nutrient deficits, which are a major limiting factor in productivity (Bote & Struik, 2011, in Rigal et al., 2020). In addition, integrated management improves nutrient use efficiency and reduces the risk of nutrient loss due to leaching. This confirms that soil fertility sustainability is not only determined by fertiliser inputs, but also by the ecological contribution of shade trees through pruning practices. Thus, coffee agroforestry systems that apply both practices can maintain long- term productivity while preserving soil quality.

The Role of Pruning and Fertilisation in Coffee Agroforestry Systems on Nutrient Balance and Soil Fertility

Pruning in coffee agroforestry systems plays an important role in maintaining nutrient balance by increasing the input of organic matter from pruning debris. Pruning debris contributes significantly to nutrient availability, thereby improving the chemical, physical, and biological properties of the soil. In addition, shade tree pruning reduces nutrient competition between coffee plants and shade trees, which ultimately optimises nutrient availability for coffee. These benefits also support a more efficient nutrient cycle, maintain soil fertility, and enhance the sustainability of coffee farming systems. Thus, pruning is not merely a plant care technique, but a nutrient management strategy that contributes to the productivity and sustainability of coffee agroforestry (Cannavo et al., 2013; Wibawa et al., 2010, in Rigal et al., 2020).

On the other hand, fertilisation serves as an additional balancing factor in the coffee agroforestry system, especially when the nutrient requirements of the plants cannot be fully met by organic inputs from litter. The application of fertilisers, both organic and inorganic, increases the availability of essential nutrients such as nitrogen, phosphorus and potassium, which are crucial during the critical growth phase of coffee. Fertiliser management tailored to the conditions of the agroforestry ecosystem has been shown to improve nutrient use efficiency while balancing the nutrient balance in the long term.

Accuracy in the type and dosage of fertiliser also prevents nutrient deficits or excesses that could potentially reduce soil fertility. Therefore, adaptive fertilisation practices are an important tool in maintaining the sustainability of coffee productivity in agroforestry lands. Thus, fertilisation should be viewed as an important complement to the ecological function of shade trees (Kairu et al., 2012; Snoeck et al., 2010, in Rigal et al., 2020).

The integration of pruning and fertilisation provides a stronger synergistic effect in maintaining nutrient balance than the separate application of either practice. Pruning increases organic matter input, while fertilisation provides nutrients that are more readily available to plants. The combination of these two practices has been proven effective in increasing nutrient use efficiency, maintaining soil fertility, and supporting sustainable coffee productivity. Research shows that integrating pruning and fertilisation can maintain nutrient balance sustainability and reduce the risk of land degradation due to nutrient deficits. In other words, this integrated management approach is an ecological and agronomic strategy that supports the resilience of the coffee agroforestry system. This emphasises the importance of integrated nutrient management in addressing the challenges of production and soil resource conservation (Rigal et al., 2018; Tully & Lawrence, 2011, in Rigal et al., 2020).

A positive nutrient balance is key to maintaining soil fertility and ensuring sustainable coffee productivity. When nutrient inputs from pruning and fertilisation are balanced with nutrient requirements and exports by the coffee harvest, the agricultural system can maintain productivity in the long term. Conversely, nutrient deficits in the soil result in a decline in fertility, which directly impacts coffee yields. Therefore, maintaining nutrient balance through appropriate management practices is a priority in coffee agroforestry. Integrated pruning and fertilisation ensure the availability of nutrients during critical growth phases, such as fruit filling, when nutrient uptake peaks. This condition confirms that the close relationship between soil fertility, nutrient balance, and coffee yield is highly dependent on sustainable nutrient management (Cannell, 1985; Vaast et al., 2006; Siles et al., 2010, in Rigal et al., 2020).

In addition to supporting coffee productivity, pruning and fertilisation in agroforestry systems also contribute to long-term ecological sustainability. Regular pruning produces litter that increases soil organic carbon reserves and improves soil structure, which has implications for increasing the soil's capacity to store water and reduce erosion. On the other hand, well-managed fertilisation prevents nutrient loss through washing and leaching, thereby maintaining the quality of the surrounding soil and water. The integration of these two practices also encourages soil microbial activity, which plays an important role in the decomposition of organic matter and nutrient cycling. Thus, pruning and fertilisation management not only maintains nutrient balance for coffee plants but also strengthens the overall function of the agroforestry ecosystem. This shows that such agronomic strategies support the resilience of agroecosystems to long-term environmental pressures (Meylan et al., 2017; van der Wal et al., 2020).

For smallholder farmers, the application of adaptive pruning and fertilisation practices has high practical relevance as it is directly related to their economic and social sustainability. Regular pruning facilitates orchard management, increases the productivity of productive branches, and reduces maintenance costs by utilising litter as natural fertiliser. Fertilisation tailored to soil conditions and plant needs also reduces input waste and production costs, thereby increasing farming efficiency. Furthermore, the balanced nutrient balance maintained through these practices ensures stable coffee productivity, providing farmers with income security. With simultaneous ecological and economic benefits, the combination of pruning and fertilisation can be considered a sustainable approach to improving the resilience of agroforestry-based coffee systems. Therefore, strengthening farmers' capacity to implement these practices is an important part of sustainable agricultural development strategies (Rigal et al., 2018; Snoeck et al., 2010).

The integration of pruning and fertilisation in coffee agroforestry systems can be understood as a form of integrated nutrient management that aims to maintain nutrient balance while preserving the sustainability of agricultural ecosystems. Pruning not only reduces nutrient competition with shade trees, but also increases organic matter input through litter, which enriches soil fertility. Meanwhile, fertilisation complements this contribution by providing more readily available nutrients to support critical growth phases, especially during the fruit filling stage. When these two practices are combined, the nutrient cycle runs more efficiently due to the synergy between organic and inorganic inputs. In the long term, this strategy prevents nutrient deficits, which are often a constraint on productivity in monoculture coffee plantations. Therefore, this integrated approach can be viewed as an agronomic innovation that is not only relevant to productivity but also important for maintaining the ecological function of agroforestry land (Cannavo et al., 2013; Rigal et al., 2018; Snoeck et al., 2010).

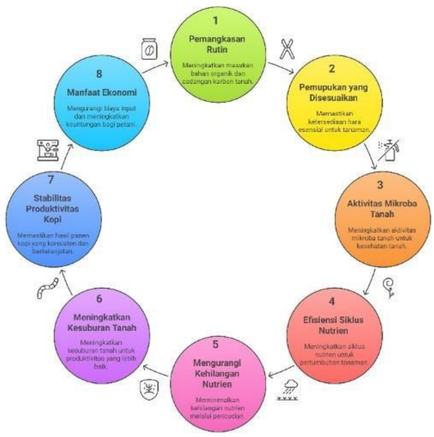

Figure 4

The Sustainable Coffee Management Cycle diagram shows that regular pruning increases organic inputs and soil carbon reserves, while tailored fertilisation ensures the availability of essential nutrients. This combination promotes soil microbial activity, improves nutrient cycle efficiency, and reduces nutrient loss. The impact is increased soil fertility, stable coffee productivity, and economic benefits through reduced input costs. Thus, the integration of pruning, fertilisation, and soil fertility management forms a more sustainable and productive coffee cultivation system (Rigal et al., 2018; Meylan et al., 2017; Kurniawan et al., 2024).

The main findings of this literature review indicate that pruning and fertilisation play complementary roles in maintaining nutrient balance in coffee agroforestry. Regular pruning has been shown to increase organic matter input and soil carbon reserves, while fertilisation tailored to plant needs maintains the availability of essential nutrients such as N, P, and K. The combination of these two practices has positive implications for increasing soil microbial activity, nutrient cycle efficiency, and reducing the risk of nutrient loss through leaching. A positive nutrient balance supports increased soil fertility and contributes directly to the long-term stability of coffee productivity. In addition, this practice provides economic benefits to smallholders by reducing input costs while ensuring consistent yields. Thus, the integration of pruning and fertilisation can be considered a key strategy in sustainable coffee management that meets both ecological and economic objectives (Vaast et al., 2006; Meylan et al., 2017; van der Wal et al., 2020).

The Relationship Between Nutrient Balance and Soil Fertility in Coffee Productivity

Nutrient balance and soil fertility are closely related in determining coffee productivity in agroforestry systems. A positive nutrient balance indicates a balance between nutrient inputs and outputs, ensuring the availability of essential nutrients for coffee plants. This balance is achieved through a combination of appropriate fertilisation practices, the addition of mulch from shade trees, and nitrogen fixation by leguminous plants. If the nutrient balance is deficient, the soil will lose essential elements, which will ultimately reduce its fertility. This condition results in reduced availability of nitrogen, phosphorus, and potassium, which are the main nutrients for coffee. Therefore, a balanced nutrient balance not only maintains soil fertility but also serves as the foundation for sustainable coffee production. This confirms that proper nutrient management is a key factor in supporting long-term coffee productivity (Vaast et al., 2006; Bote & Struik, 2011; Siles et al., 2010).

Soil fertility itself is largely determined by organic matter content, soil pH, and the activity of microorganisms that affect nutrient availability. The coffee agroforestry system can improve soil fertility through the input of litter and pruning residues, which improve the physical, chemical, and biological properties of the soil. The practice of pruning shade trees also plays a role in reducing nutrient competition and improving nutrient cycle efficiency. Thus, soil fertility can be maintained sustainably, supporting critical growth phases in coffee, especially during fruit filling, which requires up to 95% NPK uptake. If soil fertility declines, coffee plants will experience a decrease in yield and even physiological damage. The causal relationship between nutrient balance, soil fertility, and coffee productivity highlights the importance of an integrated nutrient management approach. The balance between fertiliser inputs, litter contributions, and natural nutrient cycles is a key factor in maintaining optimal coffee productivity (Cannell, 1985; Rigal et al., 2018; van der Wal et al., 2020).

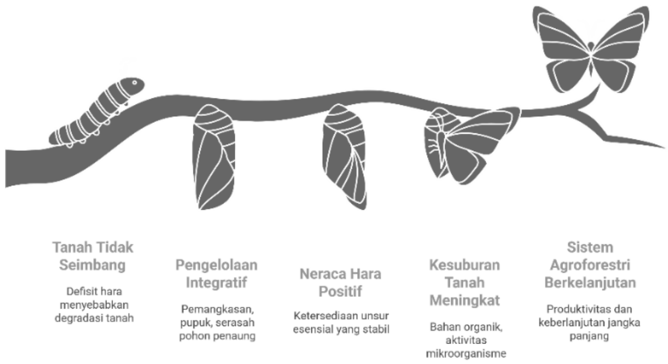

Figure 6

The figure depicts the transformation of the coffee agroforestry system through the analogy of butterfly metamorphosis. The initial condition is unbalanced soil due to nutrient deficits that reduce fertility. Through integrated management practices such as pruning, fertilisation, and mulching with shade tree litter, a positive nutrient balance is created that maintains the availability of essential elements. This increases soil fertility through organic matter and microorganism activity. In the final stage, the agroforestry system achieves sustainability with high and stable productivity in the long term (Meylan et al., 2017; Rigal et al., 2018; Siles et al., 2010; Van Asten et al., 2011; Matondang et al., 2025).

The relationship between nutrient balance and soil fertility in coffee agroforestry systems shows a mutually reinforcing relationship that supports crop productivity. A positive nutrient balance maintains the stability of essential elements, especially nitrogen, phosphorus, and potassium, which are crucial for the growth and fruit filling phases of coffee. Under balanced nutrient balance conditions, soil fertility can be maintained through increased organic matter content, microorganism activity, and nutrient cycle efficiency. Conversely, nutrient deficits accelerate soil fertility degradation, leading to reduced yields. This analysis emphasises the importance of integrated management practices, including pruning, applying organic and inorganic fertilisers, and utilising shade tree litter, to maintain the balance of the coffee land ecosystem. Thus, adaptive nutrient balance management not only increases productivity but also ensures the sustainability of the coffee agroforestry system. This relationship is in line with findings that a maintained nutrient balance is the basis for long-term sustainability of coffee production (Siles et al., 2010; Rigal et al., 2018; Vaast et al., 2006).

A review of the literature shows that a positive nutrient balance contributes significantly to increased soil fertility and is directly correlated with coffee productivity. During the fruit filling phase, nutrient requirements increase to 95% of total uptake, so the availability of nutrients in the soil is crucial to successful production. The practice of pruning shade trees has been shown to increase litter input, which enriches soil organic matter, while proper fertilization balances the nutrient requirements of coffee with the available supply. These findings also highlight that nutrient imbalances, whether due to under- or over-fertilization, can reduce nutrient use efficiency and worsen soil fertility conditions. Well-managed coffee agroforestry has been shown to maintain nutrient cycles, reduce the risk of nutrient loss, and maintain long-term productivity. Thus, the success of agroforestry coffee systems is largely determined by the integration of pruning, fertilization, and organic litter contributions in maintaining nutrient balance and soil fertility. This is consistent with research findings emphasizing the fundamental role of nutrient balance and soil fertility in coffee productivity (Cannell, 1985; Bote & Struik, 2011; van der Wal et al., 2020).

The results of the study indicate that pruning and fertilization in coffee agroforestry systems are highly effective in maintaining soil fertility, balancing nutrient levels, and ultimately increasing coffee productivity. Pruning contributes organic litter that enriches carbon reserves and improves soil structure, while fertilization increases the availability of essential macronutrients such as nitrogen, phosphorus, and potassium. The integration of these two practices has been shown to result in a positive nutrient balance, which has implications for increased microbial activity, soil respiration, and nutrient cycle efficiency. Furthermore, the relationship between nutrient balance and soil fertility has been shown to be significant in determining coffee yields, especially during the critical fruit filling phase. Thus, this study directly answers the research question posed, namely, the effectiveness of pruning and fertilization in maintaining fertility, nutrient balance, and the relationship between the two and coffee productivity.

The research findings are consistent with the theoretical framework that views pruning as an important agronomic strategy to increase light penetration, reduce branch competition, and improve microclimate. Azizah et al. (2023) emphasize that pruning supports the regeneration of new, healthy branches, and this is supported by a literature synthesis showing increased coffee productivity in pruned plants. Similarly, Kurniawan et al. (2024) theory regarding the increase in total nitrogen due to pruning is consistent with the results of field studies. In terms of fertilization, the results of the study reinforce the classic theories of Malavolta (1990) and Schnug et al. (1996) on the importance of fertilisation in replacing nutrients lost due to harvesting, while also confirming the findings of Putri et al. (2018) that organic and inorganic fertilisers need to be combined for sustainable results.

However, there are some interesting differences with previous literature. Rossi et al. (2011) emphasize the risk of long-term degradation due to excessive inorganic fertilizers, while the results of this SLR show that these negative impacts can be mitigated through a combination with organic inputs. In other words, this synthesis expands the theoretical framework by adding an integrative perspective that has not been widely explored in previous studies. A new contribution is also evident in the explicit link between nutrient balance and coffee productivity, which in the classical literature (e.g. Cannell, 1985) has been discussed more separately.

The synthesis shows that the two practices complement each other: pruning adds litter that enriches organic matter and improves soil structure, while fertilisation increases the availability of macro and micro nutrients. Soil microbial activity increases significantly with this combination of inputs, indicating a strengthening of ecosystem function. Pruning reduces nutrient competition between plants, while fertilisation balances nutrient requirements during critical growth phases. The combination of the two ensures a positive nutrient balance, which has been shown to be closely related to long-term productivity. This synthesis confirms that a single approach is not sufficient and that an integrative strategy is needed. A positive nutrient balance has been shown to improve soil fertility chemically, physically, and biologically, which has implications for productivity. The coffee fruit filling phase, which requires up to 95% NPK uptake, is important evidence that successful productivity is highly dependent on the integration of nutrient balance and soil fertility.

Theoretically, these findings expand the agronomic framework by emphasising the importance of ecological interactions between pruning, fertilisation, and soil nutrient dynamics. The resulting conceptual model can be considered an improvement on classical agronomic theory, which tended to separate pruning from fertilisation. This study also enriches the discourse on agroecology by showing how simple practices can build the resilience of agricultural systems to soil degradation and climate change.

The practical implications for coffee farmers are clear. Regular pruning and adaptive fertilisation have been shown to reduce input costs while increasing yields. Smallholders can utilise litter as natural fertiliser, reducing their dependence on chemical fertilisers and ensuring the sustainability of their farming businesses. From a policy perspective, these results support the importance of agricultural extension programmes that emphasise integrated practices, the provision of organic fertiliser subsidies, and the promotion of agroforestry as a national strategy for food security and climate change mitigation.

One relatively surprising finding was that pruning not only affected light penetration and branch regeneration, but also significantly increased the total nitrogen content of the soil. This confirms that pruning residues play a greater role than expected, namely as a long-term source of nutrients. In addition, the finding that a combination of pruning and organic-inorganic fertilisation can increase coffee yields by up to 20 times (Fitra et al., 2024) is far above expectations. This can be explained by the synergy between improved soil structure, increased water storage capacity, and efficient nutrient use during the critical phase of coffee growth.

The SLR methodology provides strength in presenting a comprehensive synthesis of various research contexts, reducing subjective bias, and increasing the validity of results through quality evaluation using MMAT. The use of NVivo 14 enables systematic thematic analysis so that patterns and relationships between variables can be identified in depth. However, limitations remain, particularly regarding the heterogeneity of research contexts, variations in fertiliser dosage and type, and different ecological conditions at each study site. In addition, although the publication range was updated to 2025, there is still potential for language bias as non-English and non-Indonesian literature was excluded.

This study identifies a gap in research that integrates socio-economic aspects with agronomic practices. Most studies still focus on biophysical aspects, while long-term cost-benefit analyses for smallholder farmers have not been widely conducted. In addition, issues of resilience to climate variability, such as prolonged droughts or extreme flooding, require further exploration. Future research needs to examine adaptive coffee agroforestry models that incorporate both climatic and economic factors. The use of interdisciplinary approaches, for example through the integration of ecological models with socio-economic analysis, will strengthen understanding and provide more applicable recommendations for sustainable agricultural policies.

CONCLUSIONS AND SUGGESTION

Conclusions

The results of this systematic review indicate that pruning and fertilisation play complementary roles in maintaining soil fertility, balancing nutrient budgets, and increasing coffee productivity in agroforestry systems. Pruning contributes through organic litter that enriches carbon reserves and improves soil structure, while fertilisation ensures the availability of essential nutrients such as N, P, and K. The integration of both practices has been shown to result in a positive nutrient balance, which has implications for increased microbial activity, nutrient cycle efficiency, and long-term productivity stability. This study expands the theoretical framework by emphasising the importance of an integrative approach, while strengthening empirical evidence that integrated practices can address the challenges of soil degradation and low productivity. However, location heterogeneity, fertiliser dose variation, and the limited availability of non-English literature pose methodological constraints that need to be considered.

Recomendations

Further research needs to integrate socio-economic aspects with agronomic dimensions to make the recommendations more applicable to smallholder farmers. The main focus going forward is the development of adaptive agroforestry models that incorporate extreme climate factors, long-term cost-benefit analysis, and the use of innovative nutrient management technologies. Practitioners require intensive training on routine pruning and adaptive fertilisation to improve cost efficiency and crop yields. Meanwhile, policymakers are advised to provide support through extension programmes, organic fertiliser incentives, and regulations that encourage sustainable agroforestry practices. Thus, further research and implementation are expected to strengthen the resilience of agroforestry-based coffee systems, ecologically, economically, and socially.

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