

Review Article

Synergistic Effects of Lime with Organic and Inorganic Fertilizers on Soil Acidity and Crop Productivity

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Abstract

Soil acidity is a critical global constraint to agricultural productivity, causing nutrient deficiencies, aluminum toxicity, and impaired microbial function. While liming is a fundamental corrective practice, its efficacy and sustainability can be significantly enhanced through integration with organic and inorganic fertilizers. This systematic review synthesizes current research on the synergistic effects of these combined amendments on soil acidity amelioration and crop productivity. Our analysis demonstrates that co-application consistently outperforms single amendments, leading to a more substantial increase in soil pH, a greater reduction in exchangeable aluminum, and improved nutrient availability and retention. These soil improvements translate directly into significant enhancements in crop growth, yield, and nutrient uptake. The mechanisms underpinning these synergies include improved lime dissolution and buffering capacity from organic matter, complexation of toxic aluminum ions, and stimulation of microbial communities that drive nutrient cycling. Furthermore, integrated nutrient management mitigates the accelerated acidification often associated with sole mineral fertilizer use. This review concludes that the judicious combination of lime, organic materials, and inorganic fertilizers represents a potent strategy for sustainable intensification of agriculture on acid soils. It offers a pathway to enhance productivity, improve long-term soil health, reduce environmental impacts, and contribute to global food security. Future research should focus on optimizing application protocols for specific agro-ecological contexts and elucidating the long-term dynamics of these interactions.

Keywords

Synergistic Effects, Organic Fertilizers, Inorganic Fertilizers, Liming, Soil Acidity

1. Introduction

Soil acidity, defined by a soil pH below 5.5, is a critical constraint to agricultural productivity across approximately 30% of the world's ice-free arable land [1-3]. This widespread phenomenon is primarily driven by natural pedogenetic processes, including the leaching of basic cations (e.g., Ca^{2+} ,

Mg^{2+} , K^{+}) and the accumulation of acidic compounds derived from organic matter decomposition and mineral weathering [4]. Beyond these natural processes, anthropogenic activities—such as continuous monocropping, the application of acidifying ammonium-based fertilizers, and industrial emis-

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sions—significantly exacerbate the rate of soil acidification [5, 6]. The direct agronomic consequences of soil acidity are multifaceted: they include reduced availability of essential nutrients (particularly phosphorus, calcium, and magnesium) and the increased solubility and phytotoxicity of elements such as aluminum and manganese, which severely inhibit root development and function, thereby impairing nutrient and water uptake [7]. Moreover, soil acidity detrimentally impacts soil microbial community structure and function, thereby impeding essential biogeochemical cycles like nitrogen fixation, nitrification, and organic matter decomposition, which are crucial for maintaining long-term soil fertility [8]. The excessive and disproportionate application of chemical fertilizers, while potentially boosting short-term crop yields, often leads to further soil chemical degradation, nutritional stress, and negative impacts on the beneficial soil microorganisms that are vital for fertility [5]. Notably, long-term application of nitrogenous fertilizers has been observed to decrease soil pH while concurrently increasing soil organic carbon and total nitrogen content, creating a complex fertility scenario [9]. Conversely, the judicious application of lime, a common liming agent, significantly increases soil pH, mitigating the toxic effects of aluminum and manganese while enhancing the bioavailability of essential nutrients for plant uptake [10].

The challenge of soil acidity is particularly prominent in humid tropical and subtropical regions, where highly weathered soils (e.g., Oxisols, Ultisols) naturally exhibit acidic conditions, substantially limiting food production in many developing nations [11]. Compounding this natural pedological setting, anthropogenic activities such as intensive agriculture, monoculture, and the overuse of chemical fertilizers—especially nitrogen-based compounds—exacerbate soil acidification, transforming it into an increasingly severe and dynamic global problem [12]. The detrimental effects, including nutrient immobilization and metal toxicity, severely impede plant physiological processes and diminish crop yields. Mitigating soil acidity is therefore paramount for achieving sustainable agricultural intensification, and liming has emerged as a cornerstone practice for restoring soil health and enhancing crop productivity [13]. However, the efficacy of liming can be substantially enhanced when integrated with organic and inorganic fertilizers, leading to more profound, balanced, and lasting improvements in soil physicochemical properties and crop performance [14, 15]. This integrated approach is vital to counteract the progressive soil acidification caused by high-rate ammonium nitrate fertilization, a process often exacerbated by the concurrent application of acidifying superphosphate and potassium salts [16]. Consequently, research into the synergistic application of liming materials with diverse organic and inorganic nutrient sources is crucial for developing robust agricultural systems capable of maintaining soil fertility and enhancing crop yields in acid-prone environments [17]. Such strategies are indispensable for ensuring long-term agricultural sustainability and mitigating the adverse environmental impacts associated with

conventional, input-intensive fertilization practices [18]. This integrated nutrient management approach not only addresses soil pH directly but also holistically improves nutrient availability, soil organic matter, and overall soil biological health, ultimately contributing to increased crop yields, enhanced farm profitability, and greater food security. Given that approximately 3.95 billion hectares of land globally are affected by soil acidity, the development and dissemination of effective amelioration strategies are of paramount importance for global agricultural output [5, 19].

In brief, soil acidity represents a formidable global constraint on agricultural productivity, particularly in regions characterized by high rainfall and the intensive application of nitrogenous fertilizers [20]. This pervasive issue precipitates diminished nutrient availability, induces aluminum (Al^{3+}) and manganese (Mn^{2+}) toxicities, and impairs microbial activity, collectively curtailing crop growth and yield potential [4]. The persistent challenges inherent in soil acidity necessitate the implementation of effective amelioration strategies. Among these, liming is a widely recognized and fundamental practice for pH correction and the enhancement of nutrient cycling [21]. While demonstrably effective, the financial cost of liming and its requirement for frequent reapplication—particularly for smallholder farmers—underscore the critical importance of exploring synergistic approaches. Integrating organic and inorganic fertilizers with lime can significantly enhance its efficacy and sustainability [22]. Furthermore, such integrated management options can improve nutrient use efficiency, bolster soil health, and mitigate the accelerated acidification often associated with the sole application of mineral fertilizers [23, 24]. This systematic review aims to synthesize contemporary research on the combined effects of lime with various organic and inorganic fertilizers on the amelioration of soil acidity and the subsequent improvements in crop productivity. It will elucidate the mechanisms underpinning these synergistic interactions and identify optimized, sustainable management practices. This review will delineate the intricate interplay between these amendments, demonstrating how their strategic co-application can lead to more stable, resilient, and enhanced crop production outcomes.

2. Materials and Methods

The search strategy employed a comprehensive and systematic methodology. It utilized a precise set of keywords related to core concepts: lime (e.g., liming, calcium carbonate, dolomite), organic amendments (e.g., biochar, compost, manure, biofertilizer), inorganic fertilizers (e.g., NPK, urea, ammonium nitrate), soil acidity (e.g., acid soil, soil pH, aluminum toxicity), and crop yield. These terms were deployed across major scientific databases, including Web of Science, Scopus, and Google Scholar, using Boolean operators (AND, OR, NOT) to refine search queries. This ensured the retrieval of highly relevant articles while minimizing extraneous re-

sults. The selection process prioritized peer-reviewed journal articles, dissertations, and conference proceedings published primarily in English, focusing on field, greenhouse, and incubation studies conducted over the past three decades (2000-2025) to capture contemporary agricultural practices and research advancements. This systematic approach ensures a robust and representative collection of studies, providing a comprehensive foundation for evaluating the synergistic effects.

Studies were included if they were published in English between 2000 and 2025 and reported original empirical data on the combined application of lime with organic (e.g., biochar, compost, manure) or inorganic fertilizers (e.g., NPK, urea). Studies focusing exclusively on single-amendment applications or those lacking quantitative data on soil chemical properties (e.g., pH, exchangeable Al) or crop performance (e.g., yield, biomass) were excluded. Furthermore, review articles, meta-analyses, theoretical papers, and studies not directly addressing soil acidity amelioration or crop productivity responses were omitted to maintain the focused scope and empirical rigor of this systematic review.

A standardized data extraction protocol was followed. The process focused on quantitative outcomes related to soil acidity parameters (soil pH, exchangeable Al³⁺, H⁺), macro- and micronutrient availability, crop biomass, yield components, and nutrient uptake. Qualitative information on experimental design (e.g., randomized complete block, pot experiment), soil type and classification, cropping system, amendment types, and application rates was also systematically extracted. This comprehensive extraction process facilitated a rigorous subsequent synthesis and meta-analysis to identify significant trends and relationships across diverse experimental conditions. Each extracted study underwent a critical appraisal to assess its methodological rigor and potential for bias, ensuring the reliability and validity of the synthesized findings.

The quality assessment process involved evaluating the methodological rigor of each selected study based on predefined criteria, including sample size, replication, the presence of appropriate control treatments, statistical analyses used, and the clarity of reporting. This appraisal framework allowed for the identification of high-quality evidence, informing the strength of conclusions drawn regarding the synergistic effects of lime with organic and inorganic fertilizers and ensuring that findings were based on methodologically sound research.

A mixed-methods approach was employed for data synthesis. A meta-analysis was conducted on quantitative data where sufficient homogeneity existed, allowing for the calculation of standardized mean differences for key parameters such as soil pH, nutrient uptake, and crop yield. This provided a quantitative, statistical basis for comparing the efficacy of different treatment combinations. For studies unsuitable for meta-analysis, qualitative data were synthesized through thematic analysis to elucidate underlying mechanisms and

contextual factors influencing the observed synergistic interactions.

3. Results

The initial search yielded a substantial number of articles. These were rigorously screened based on titles and abstracts for relevance to the review's scope. Following this preliminary screening, a total of 150 full-text articles were retrieved and subjected to a detailed evaluation against the predefined inclusion and exclusion criteria. Ultimately, 85 studies met all criteria and were included in the final qualitative and quantitative synthesis. This corpus of literature encompasses a wide range of crop types, soil conditions, and experimental designs. The rigorous selection process ensured the robustness and representativeness of the dataset, enabling a comprehensive analysis of the synergistic effects.

The characteristics of the included studies exhibited significant variation, reflecting the global nature of the issue. They encompassed diverse geographical locations, with a focus on tropical and subtropical regions where acid soils are prevalent. Soil types investigated ranged from highly weathered and acidic Oxisols and Ultisols, characterized by low base saturation and high aluminum toxicity, to more fertile but still acidic Alfisols and Inceptisols. Cropping systems evaluated included staple food crops such as maize, rice, and wheat, alongside cash crops like tea and coffee. The research designs represented included field experiments, greenhouse trials, and laboratory incubations, providing a robust and multifaceted dataset for assessing the interactions between lime and various fertilizer types.

3.1. Effects on Soil Acidity Amelioration

The results consistently demonstrated that the co-application of lime with both organic and inorganic fertilizers significantly enhanced soil pH, reduced exchangeable aluminum and hydrogen ions, and improved cation exchange capacity more effectively than single applications of these amendments. This synergistic effect was particularly pronounced in highly acidic soils, where the presence of organic matter facilitated lime dissolution and improved its buffering capacity [14]. Moreover, the organic components contributed to the detoxification of aluminum through the formation of stable organo-aluminum complexes, further alleviating this major constraint to root growth in acidic soils. Beyond direct pH amelioration, the interaction between lime and organic amendments also stimulated microbial activity and biomass, leading to enhanced nutrient cycling and improved soil structure [25]. The rapid neutralization of soil acidity observed with certain reactive liming materials, such as papermill lime-sludge, highlights their efficiency in achieving maximum pH elevation within a shorter timeframe compared to conventional agricultural limestone, attributable to their finer particle size and higher reactivity [26]. Furthermore, the

efficacy of various alternative liming materials, including biochar and wood ash, was found to be comparable or even superior to traditional lime in some contexts, due to these properties and their additional benefits such as nutrient retention and microbial community modulation [27]. The addition of organic compounds, particularly those with a high anion-to-acid ratio, can also directly increase soil pH through the biochemical decarboxylation of organic anions and the consumption of protons during decomposition [17].

3.2. Effects on Crop Productivity

The integrated use of lime and nutrient amendments consistently led to significant increases in crop yields, biomass, and nutrient uptake across a variety of agricultural systems [28, 29]. Lime, when combined with organic fertilizers, not only boosted crop production but also enhanced nutrient use efficiency, leading to higher overall productivity [30]. For instance, the application of dolomite with organic amendments significantly reduced exchangeable aluminum and increased soil pH, thereby directly improving soybean yields [31, 32]. This enhancement is largely attributed to the improved availability of essential nutrients like phosphorus and molybdenum, which are typically fixed or less accessible in acidic conditions [33]. Furthermore, the amelioration of aluminum toxicity allows for improved root architecture and proliferation, facilitating greater exploration of the soil volume for water and nutrients, which directly translates into enhanced crop performance [34]. This integrated approach simultaneously addresses multiple soil constraints, making it a highly effective strategy for sustainable agricultural intensification in acid-prone regions [35, 36]. Such strategies are crucial given that soil acidity impedes crop growth on a significant portion of the world's arable land by inducing aluminum toxicity and limiting nutrient availability [37]. Addressing this widespread challenge requires comprehensive approaches that not only neutralize acidity but also enhance overall soil health and fertility. The continuous and excessive application of chemical fertilizers, a common practice in modern agriculture, exacerbates soil acidification, leading to nutrient imbalances and diminished soil quality, thereby highlighting the necessity for integrated fertilization strategies [38].

3.3. Synergistic Effects Analysis

A deeper analysis revealed that the integrated application of lime with organic amendments, such as manure or crop residues, significantly improved soil nitrogen mineralization kinetics, leading to enhanced nitrogen availability for crops [35]. Similarly, the co-application of lime with inorganic nitrogen fertilizers, such as urea, while potentially contributing to a slight initial acidification, proved to be a more cost-effective and agronomically efficient strategy for farmers when coupled with regular liming, ultimately optimizing

nutrient supply and crop yield. This synergistic approach also mitigated the negative effects of nitrogen fertilization on soil pH, maintaining a more favorable environment for microbial activity and nutrient cycling [39, 40]. The integration of organic amendments (e.g., farmyard manure, vermicompost) with inorganic fertilizers and lime has been shown to optimize soil properties, including nutrient retention and availability, leading to greater yield stability and higher productivity [15, 28]. This combined strategy improves nutrient use efficiency, enhances soil organic matter content and cation exchange capacity, and is crucial for long-term soil health [14]. This INM approach also mitigates the adverse effects of excessive chemical fertilizer use on ecological health and soil microbiota, thereby promoting more sustainable agricultural practices [35, 41, 42]. This holistic approach is vital given widespread issues of nutrient deficiency and declining soil quality. Moreover, biofertilizers (e.g., phosphorus-solubilizing bacteria, nitrogen-fixers) represent a crucial component of this integrated strategy, as they enhance nutrient availability through biological processes, reducing reliance on synthetic inputs while improving soil fertility [43]. This can lead to significant improvements in nutrient uptake, pathogen resistance, and overall soil productivity [44]. This integrated approach, which combines organic, inorganic, and biological nutrient sources, is increasingly recognized for its superior potential to improve nutrient use efficiency and reduce environmental impacts compared to the sole use of inorganic fertilizers [45]. Such multi-faceted strategies are indispensable for achieving sustainable agricultural intensification, particularly in regions facing severe soil degradation [46]. These systems foster a balanced nutrient regime and improved soil structure, laying the groundwork for long-term agricultural resilience against environmental stressors [5, 42].

4. Discussion

This section delves into the mechanisms underlying the observed synergistic effects, exploring how the combined application optimizes soil chemical, physical, and biological properties to enhance plant growth. Liming primarily neutralizes acidity, but it also enhances the efficacy of both organic and inorganic fertilizers by improving nutrient availability and reducing the toxicity of aluminum and manganese. The increased soil pH from liming can enhance the cation exchange capacity of variable-charge soils, particularly in highly weathered tropical soils, thereby improving the retention of base cations and preventing their leaching [47]. Furthermore, the combination of lime with organic amendments fosters a more robust and diverse soil microbial community, which in turn facilitates nutrient mineralization, accelerates nutrient cycling, and improves soil aggregation and structure [48]. This improved microbial activity enhances the decomposition of organic matter, releasing a steady supply of nutrients for plant uptake and mitigating potential short-term nutrient immobilization [49]. These multifaceted interactions

collectively contribute to a more resilient and productive agroecosystem, underpinning long-term sustainability. The enhanced soil fertility and reduced environmental impact achieved through these integrated approaches underscore their importance in promoting sustainable intensification. This synergistic effect can lead to improved crop resilience against environmental stressors and reduced reliance on synthetic inputs, aligning with ecological farming principles [44]. The application of organic amendments, such as manure compost, improves soil physicochemical properties, increases soil organic matter content, and enhances CEC, thereby stabilizing heavy metals and improving overall soil health [22]. This further underscores the importance of integrating bio-fertilizers and other microbial inoculants, which enrich the soil with beneficial microorganisms, enhancing nutrient cycling and plant growth promotion. These biofertilizers improve plant growth by increasing native nutrient bioavailability, producing antibacterial and/or antifungal substances, and enhancing the activity of indigenous soil microorganisms [50]. This intricate interplay between liming, organic amendments, and microbial activity establishes a self-reinforcing cycle of improved soil health and sustained productivity, reducing reliance on external inputs [51]. This is critical given that conventional practices reliant on inorganic fertilizers often lead to diminished soil microbial diversity and compromised soil health over time [52]. The judicious integration of biofertilizers serves to bolster the rhizosphere's microbial population, thereby enhancing nutrient availability and acquisition while mitigating adverse soil conditions [53]. These microbial inoculants foster beneficial communities, increase nutrient availability, improve soil structure, and reduce dependence on synthetic inputs [54-56]. This integration offers a pathway toward ecological restoration and enhanced agricultural sustainability [57]. These microorganisms, through mechanisms like nitrogen fixation, phosphate solubilization, and production of plant growth-promoting substances, play a pivotal role in augmenting crop yield and resilience [58]. They act as an eco-friendly and cost-effective substitute for synthetic fertilizers, contributing to soil health and biodiversity conservation [59]. The strategic incorporation of biofertilizers represents a critical advancement towards sustainable agriculture by minimizing ecological footprints and promoting long-term soil viability [60]. This approach not only addresses immediate nutritional demands but also cultivates a resilient, self-regulating soil ecosystem [3, 5]. This shift towards biological inputs is a sustainable alternative to conventional agrochemicals, offering a path to increased production without further environmental degradation [61]. This integration aligns with the broader goal of sustainable agriculture, emphasizing practices that maintain ecological balance and ensure food security [14]. These bioproducts enhance soil-plant interactions by solubilizing nutrients and producing phytohormones, thereby boosting productivity and promoting sustainable practices [21].

This comprehensive understanding provides a robust

foundation for developing INM strategies that are both environmentally sound and economically viable. Future research should focus on optimizing the precise ratios, types, and application timings of these amendments to maximize their beneficial interactions under specific soil and climatic conditions. Such investigations are crucial for developing region-specific recommendations. The continuous application of lime, however, warrants careful consideration due to potential long-term impacts on soil aggregate structure and increased susceptibility to leaching, which may compromise its benefits over time [62, 63]. Further research is needed on the long-term impacts of continuous lime application on soil health and microbial communities [64]. Additionally, the integration of specialized biofertilizers presents a promising avenue for further enhancing the efficacy of lime and fertilizer applications by promoting nutrient cycling and availability [44]. These microorganisms can augment nutrient uptake efficiency, reduce reliance on synthetics, and foster resilience [65]. This holistic approach aligns with the principles of sustainable agriculture, aiming to improve soil health, enhance productivity, and mitigate environmental degradation [66]. This integrated strategy represents a pivotal shift towards ecological intensification, addressing the urgent need for enhanced food security while preserving natural resources [67]. The global imperative for increased food production, coupled with the adverse environmental impacts of conventional fertilization, necessitates innovative approaches to optimize nutrient use efficiency [68]. This review synthesizes knowledge on these synergistic effects, highlighting their potential and underscoring the importance of such integrated strategies in promoting sustainable agriculture [69, 70]. A deeper understanding of these complex interactions will facilitate the development of more resilient and productive agricultural systems capable of meeting future food demands sustainably [71, 72].

The findings of this review align with and reinforce previous studies that emphasize the critical importance of integrated nutrient management for achieving sustainable agriculture. Specifically, extant literature consistently shows that the combined application of liming materials with organic and inorganic fertilizers leads to superior outcomes in terms of soil fertility enhancement and crop yield optimization compared to their individual applications. For instance, research confirms that liming not only ameliorates soil acidity but also enhances the availability of phosphorus from both organic and inorganic sources through reduced fixation onto soil colloids and improved microbial-mediated solubilisation [13]. Furthermore, the synergy between lime and phosphorus-solubilizing microorganisms has been highlighted as a promising biotechnological alternative to further enhance phosphorus availability in acidic soils where fixation is a major constraint. This approach reduces reliance on conventional P fertilizers, which often have adverse environmental effects, by promoting biological solubilisation [73]. This synergy also extends to nitrogen cycling, where the combined

application can optimize conditions for nitrogen-fixing bacteria and reduce denitrification losses. This integrated approach, leveraging chemical, organic, and biological inputs, presents a comprehensive strategy for sustainable agricultural intensification [74].

The adoption of such integrated strategies is paramount for achieving sustainable agricultural production by enhancing nutrient use efficiency and minimizing the environmental footprint associated with conventional farming [75]. This approach significantly reduces nutrient losses through leaching and runoff, thereby protecting water bodies from eutrophication and mitigating greenhouse gas emissions (e.g., N_2O) from agricultural fields [76]. Moreover, these INM practices contribute to the sequestration of atmospheric carbon dioxide through enhanced biomass production and soil organic matter accumulation, supporting climate change mitigation efforts. This holistic approach offers a robust framework for improving soil health, increasing crop productivity, and fostering ecological resilience [77, 78]. Ultimately, these synergistic strategies provide a pathway towards a more sustainable and productive agriculture by fostering healthier soils and reducing dependence on external inputs. This nuanced understanding is critical for developing region-specific recommendations that optimize outputs while safeguarding environmental integrity. This review contributes significantly to the existing body of knowledge by elucidating the multifaceted benefits of such integrated approaches.

5. Limitations

Despite the extensive nature of this review, certain limitations warrant consideration. The primary limitation concerns the inherent variability in experimental conditions and methodologies across the included studies. This heterogeneity (e.g., in soil types, climate, crop varieties, amendment forms and rates) makes direct comparisons challenging and necessitates a cautious interpretation of the aggregated findings, as universal recommendations are difficult without localized validation. Additionally, a notable limitation is the relatively limited number of long-term studies (>10 years) that comprehensively evaluate the cumulative effects of these integrated practices on soil health parameters, such as microbial diversity and long-term nutrient balance.

6. Future Research Directions

Future research should prioritize long-term field trials across diverse agro-ecological zones to validate the efficacy of integrated lime and fertilizer management strategies under real-world conditions. Such investigations are crucial for developing site-specific recommendations. Furthermore, an emphasis on the economic viability, scalability, and social acceptance of these integrated approaches is imperative to facilitate their widespread adoption by farmers, ensuring

sustainability from both an environmental and socio-economic perspective. Moreover, future studies should delve deeper into the mechanisms underlying the synergistic interactions, potentially leveraging advanced analytical techniques such as metagenomics, metabolomics, and high-throughput sequencing to elucidate microbial community shifts, nutrient transformation pathways, and the molecular basis of plant-soil-microbe interactions in ameliorated acidic soils.

7. Conclusion

In conclusion, this systematic review unequivocally demonstrates that the judicious combination of lime with organic and inorganic fertilizers represents a potent and multifaceted strategy for ameliorating soil acidity and significantly enhancing crop productivity. This integrated nutrient management approach addresses immediate nutritional demands while contributing substantially to the long-term sustainability of agricultural systems by improving soil health, structure, and nutrient use efficiency. It highlights the importance of tailored interventions that consider specific soil characteristics and crop requirements to maximize synergistic benefits. Furthermore, the adoption of INM practices reduces the need for sole reliance on chemical fertilizers, leading to improved soil properties and a reduced environmental footprint. This review thus underscores the potential of an integrated approach to fertilizer application and soil amendment for fostering resilient agricultural landscapes. The insights gained offer valuable guidance for policymakers and agricultural practitioners aiming to optimize crop yields while safeguarding environmental integrity. This comprehensive understanding positions integrated soil fertility management as a cornerstone for sustainable global food production systems.

7.1. Summary of Findings

The findings consistently demonstrate that liming effectively mitigates soil acidity by increasing pH, which subsequently enhances the availability of essential nutrients such as phosphorus, potassium, calcium, and magnesium for plant uptake. Simultaneously, the incorporation of organic fertilizers enriches soil organic matter content, fosters microbial activity, and improves cation exchange capacity, thereby bolstering the soil's inherent nutrient retention and supply capabilities. Inorganic fertilizers provide a rapid and precise influx of readily available nutrients, addressing immediate crop demands and ensuring robust growth. The synergistic application of all three components creates an optimal rhizosphere environment that maximizes nutrient uptake efficiency, promotes beneficial microbial activity, and leads to sustained high yields. This integrated approach not only elevates crop productivity but also mitigates the negative environmental impacts (e.g., leaching, runoff, emissions) often

associated with the exclusive use of synthetic fertilizers. This holistic strategy aligns with the principles of sustainable agriculture by promoting soil health, enhancing nutrient cycling, and reducing the ecological footprint of farming. Furthermore, this integrated system contributes to the reduction of nutrient leaching and runoff, thereby protecting water quality, and can reduce greenhouse gas emissions associated with fertilizer production and application. Such practices enhance the resilience of agricultural systems to climate variability and improve overall soil quality, which is crucial for long-term food security.

7.2. Practical Recommendations

Based on these findings, practical recommendations for farmers and agricultural stakeholders include:

- 1) *Develop Site-Specific Programs*: Implement liming and fertilization programs tailored to local soil test results (soil pH, exchangeable Al, nutrient status) and specific crop requirements. This precision approach minimizes over-application, prevents potential nutrient imbalances, and reduces the risk of environmental pollution.
- 2) *Incorporate Organic Amendments*: Strategically incorporate organic amendments (e.g., compost, manure, quality biochar) alongside inorganic fertilizers and lime. This practice is recommended to foster a healthy and diverse soil microbiome, improve soil structure, water retention, and provide a slow-release nutrient source.
- 3) *Adopt Adaptive Management*: Emphasize continuous monitoring of soil health indicators and adopt adaptive management practices to refine these strategies over time, accounting for evolving environmental conditions, crop rotations, and new genetic varieties.

7.3. Concluding Remarks

These integrated strategies not only boost immediate agricultural output but also lay the groundwork for long-term soil health, ensuring the sustained productivity of arable lands for future generations. The adoption of such nuanced and adaptive approaches will be instrumental in achieving global food security while simultaneously preserving ecological integrity. This holistic perspective underscores the necessity of interdisciplinary research and collaboration among agronomists, soil scientists, ecologists, economists, policy-makers, and farmers to translate these findings into actionable, scalable solutions. Such a comprehensive and collaborative effort is vital for developing the sustainable agricultural systems needed to meet the increasing global food demand while mitigating environmental degradation. Future research must continue to delve into the precise mechanisms through which lime and diverse fertilizer combinations interact at a molecular and microbial level, potentially leveraging advanced omics technologies to characterize microbial responses and nutrient transformation pathways in unprecedented detail.

Abbreviations

CEC	Cations Exchange Capacity
INM	Integrated Nutrient Management

Author Contributions

Abu Regasa: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing

Wassie Haile: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Supervision, Writing – original draft, Writing – review & editing

Girma Abera: Conceptualization, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing

Data Availability Statement

Data will be made available from the corresponding author on request.

Conflicts of Interest

The authors declare no competing interests.

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