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Responses of Contrasting Tropical Soil Orders to Silica Enriched Biochar Application: A Systematic Review of Soil Fertility Implications

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ABSTRACT

Silica enriched biochar has emerged as a promising amendment for improving fertility in highly weathered tropical soils; however, its effectiveness varies considerably among soil orders due to differences in mineralogy, weathering intensity, and nutrient retention characteristics. This systematic review evaluated the responses of contrasting tropical soil orders, particularly Ultisols, Oxisols, Inceptisols, and Entisols, to silica enriched biochar application and synthesized the dominant mechanisms influencing soil fertility improvement. The review followed the PRISMA framework using literature retrieved from Scopus and ScienceDirect databases published between 2016 and 2026. A total of 875 records were initially identified, of which 32 studies fulfilled the inclusion criteria and were analyzed qualitatively. The findings demonstrated that silica-enriched biochar improved multiple soil fertility parameters through acidity neutralization, enhanced cation exchange capacity, nutrient retention, and silicon-mediated phosphorus mobilization. In Oxisols, available silicon increased from 36 to 209 mg kg^{-1}, while water retention improved by up to 30%. In Ultisols, soil pH buffering capacity increased by more than 67%, accompanied by significant increases in soil organic carbon, total nitrogen, and available phosphorus. Entisols showed substantial improvements in nutrient availability, with soil P, N, and K increasing by approximately 72%, 52%, and 33%, respectively, while maize yield increased by up to 93%. Overall, silica enriched biochar demonstrated strong potential to enhance soil fertility, nutrient use efficiency, and crop productivity in tropical agroecosystems, although its effectiveness remained highly dependent on soil-specific characteristics and biochar properties.

KEYWORDS: nutrient buffering, soil-spesific ameliorant, tropical pedogenesis

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1. INTRODUCTION

Global agriculture is increasingly confronted with severe land degradation and declining soil fertility, both of which threaten the sustainability of food production systems. In tropical regions, intensive agricultural practices that are not accompanied by sustainable soil management frequently accelerate soil quality deterioration [27]. Soil degradation is commonly characterized by losses of soil organic matter, nutrient leaching, increasing soil acidity, low cation exchange capacity (CEC), and elevated toxicity of aluminum (Al) and iron (Fe) [61]. However, the severity of these constraints varies considerably among soils due to differences in pedogenic processes, parent materials, climatic conditions, and weathering intensity. Such variability reflects the intrinsic characteristics of different soil orders, which strongly influence nutrient dynamics, soil fertility status, and responses to soil amelioration strategies [51].

Within the Soil Taxonomy framework, Ultisol and Oxisol represent highly weathered tropical soils that commonly exhibit severe fertility limitations. Ultisols are widely distributed across tropical and subtropical regions, accounting for approximately 8.1% of the global land surface, and are generally characterized by acidic conditions, low base saturation, and high concentrations of exchangeable Al that restrict root development and nutrient uptake [15]. Oxisols occupy nearly 7.5% of the global land surface and are dominated by low-activity clay minerals and sesquioxides that strongly adsorb phosphorus (P), thereby limiting its availability to plants [45]. In contrast, Inceptisol and Entisol are relatively young soils with weaker profile development and more variable fertility characteristics. Entisols, which cover nearly 18% of the global land surface, frequently exhibit coarse texture, low organic matter content, weak nutrient retention, and poor water-holding capacity [10]. These contrasting physicochemical and mineralogical characteristics indicate that soil amendment technologies are unlikely to produce uniform effects across different soil orders.

Biochar has emerged as a promising soil amendment for improving soil quality and sustaining agricultural productivity. Produced through biomass pyrolysis under oxygen-limited conditions, biochar can increase soil pH, enhance CEC, improve water retention, and reduce nutrient losses [22, 28]. Nevertheless, its effectiveness remains highly soil-specific and largely depends on interactions between biochar properties and the inherent characteristics of the target soil [4]. In highly weathered soils such as Ultisols, alkaline biochar may effectively neutralize soil acidity and reduce Al toxicity, whereas in coarse-textured soils such as Entisols, biochar may primarily improve water and nutrient retention through its porous structure. These findings highlight the importance of understanding soil order-specific responses to biochar application.

Recent advances in soil amendment technology have encouraged the development of engineered functional biochar, including silica enriched biochar. Silicon (Si) has been increasingly recognized for its role in improving plant tolerance to biotic and abiotic stresses, enhancing nutrient use efficiency, and stabilizing soil structure [32]. In soil systems, Si can also mitigate Al and Fe toxicity through the formation of insoluble aluminosilicate complexes [17]. Since highly weathered tropical soils commonly experience severe silica depletion due to prolonged leaching, silica enriched biochar offers a synergistic approach by combining the structural benefits of biochar with the gradual release of plant-available Si. Previous studies have reported that silica-associated biochar amendments can improve nutrient availability and reduce phosphorus fixation in acidic tropical soils [38].

Despite its considerable potential, the mechanisms governing the interactions between silica enriched biochar and different soil orders remain insufficiently understood. Variations in soil mineralogy, sesquioxide content, buffering capacity, and initial organic carbon status are expected to produce differential responses in nutrient dynamics and soil fertility improvement. Previous studies suggest that silica enriched biochar may enhance soil pH and reduce exchangeable Al toxicity in Ultisols, while dissolved Si in Oxisols may compete with phosphate ions at sorption sites and subsequently increase P availability [50]. In coarse-textured Entisols, the porous carbon matrix of biochar may function as an important reservoir for retaining water and nutrients, thereby reducing nutrient losses through leaching. However, most previous studies have focused only on individual soil systems or specific cropping conditions, limiting broader mechanistic understanding of soil-specific responses [47, 60].

A substantial research gap therefore remains regarding how inherent soil order characteristics regulate the effectiveness of silica enriched biochar in improving soil fertility. Comparative evaluations across highly weathered soils such as Ultisols and Oxisols and younger soils such as Inceptisols and Entisols remain limited. Accordingly, this review aims to comparatively evaluate the responses of contrasting soil orders to silica enriched biochar application, analyze changes in key soil fertility indicators, and synthesize the dominant mechanisms underlying soil-specific responses to the amendment. The findings of this review are expected to provide new insights into mineral–biochar–silica interactions while supporting the development of soil order-specific fertility management strategies for sustainable tropical agriculture.

2. MATERIALS AND METHODS

2.1 Study Design

This study employed a Systematic Literature Review (SLR) approach to comprehensively evaluate the differential responses of various soil orders to silica enriched biochar application and their implications for soil fertility improvement. The Systematic Literature Review method is widely used to identify, evaluate, and synthesize existing scientific evidence in a transparent, structured, and reproducible manner [26, 52]. The review was conducted following the guidelines of PRISMA to ensure transparency, reproducibility, and systematic article selection procedures [40]. The study focused on identifying, synthesizing, and critically comparing previous findings related to the interactions between silica enriched biochar and contrasting soil orders, particularly Ultisol, Oxisol, Inceptisol, and Entisol. The review emphasized changes in soil chemical and physical fertility indicators following biochar application.

2.2 Search Strategy and Keyword Pairs

The literature search was conducted using a structured and systematic strategy to ensure comprehensive identification of relevant peer-reviewed studies related to silica enriched biochar and its effects on different soil orders. The search process was performed across internationally recognized scientific databases, namely Scopus and ScienceDirect, due to their extensive coverage of high-quality publications in soil science, environmental science, and agricultural research. A combination of carefully selected keywords representing the major thematic components of the study, including biochar modification, silicon enrichment, soil fertility, and soil orders, was employed using Boolean operators (AND, OR) to construct comprehensive yet targeted search strings (Table I).

Table I: Search strategy and keyword combinations used to retrieve relevant studies

Search Strategies	Scopus	ScienceDirect
("biochar") AND ("silica" OR "silicon") AND ("soil fertility" OR "soil health" OR "nutrient")	50	346
("biochar") AND ("silica" OR "silicon") AND ("soil type" OR "soil properties" OR "soil characteristics")	10	72
("Si-biochar" OR "silicon biochar") AND ("soil") AND ("fertility" OR "yield" OR "biomass" OR "plant growth")	39	25
("biochar") AND ("silica" OR "silicon") AND ("soil order" OR "classification" OR "taxonomy")	5	297
("Si-biochar" OR "silicon biochar") AND ("soil") AND ("cation exchange capacity" OR "carbon" OR "pH" OR "phosphorus")	6	25
Total	875	

The search strategy integrated synonymous and closely related terminologies to maximize article retrieval while maintaining logical consistency and thematic relevance across databases. The primary search terms included combinations of “biochar”, “silica”, “silicon”, “Si-biochar”, “silicon biochar”, “soil fertility”, “soil health”, “soil properties”, “soil characteristics”, “soil type”, “soil classification”, and several soil fertility indicators such as “cation exchange capacity”, “carbon”, “pH”, and “phosphorus”. Additional agronomic-related terms including “yield”, “biomass”, and “plant growth” were also incorporated to capture studies evaluating the broader impacts of silicon-associated biochar application on soil and crop performance.

2.3 Inclusion and Exclusion Criteria

To ensure the relevance, consistency, and scientific quality of the reviewed literature, predefined inclusion and exclusion criteria were established prior to the article screening process. These criteria were designed to systematically filter studies that aligned with the objectives of this review, particularly those discussing the effects of silica- or silicon-associated biochar on soil fertility under different soil conditions. The selection criteria also aimed to minimize bias and improve the reliability of the synthesized findings by excluding studies lacking sufficient methodological rigor or relevance presented in Table II.

Table II: Criteria used to define the scope and eligibility of studies in the systematic review.

Criteria	Inclusion Criteria	Exclusion Criteria
Topic relevance	Studies focusing on silica- or silicon-associated biochar and their effects on soil fertility, soil properties, nutrient dynamics, or crop performance under different soil conditions	Studies unrelated to biochar, silicon-associated amendments, or soil fertility improvement
Type of publication	Peer-reviewed journal articles	Conference papers, reports, theses, dissertations, and book chapters
Language	Articles published in English	Non-English publications
Time range	Studies published between 2016 and 2026	Studies published outside the selected time frame
Study design	Empirical studies, including laboratory experiments, incubation studies, greenhouse trials, and field experiments	Opinion papers without empirical or analytical basis
Accessibility	Full-text articles accessible for detailed evaluation	Articles with inaccessible full text

The inclusion criteria focused on peer-reviewed original research articles that evaluated biochar applications related to silicon or silica compounds and reported measurable soil fertility indicators, such as soil pH, cation exchange capacity (CEC), soil organic carbon, nutrient availability, exchangeable bases, or other relevant soil properties. Studies examining agronomic responses, including plant growth, biomass production, or nutrient uptake, were also considered when associated with soil fertility improvement. Meanwhile, exclusion criteria were applied to remove studies that were not directly relevant to the scope of the review, including review articles, conference proceedings, theses, editorials, and studies lacking sufficient experimental or methodological information.

2.4 Article Screening and Selection

The article selection process in this systematic literature review was conducted using the PRISMA 2020 framework to ensure a transparent and structured screening procedure. Literature was collected from several scientific databases using keywords related to silica enriched biochar, tropical soils, soil fertility, and soil orders. The identification, screening, eligibility assessment, and inclusion processes were carried out systematically to obtain studies that were highly relevant to the objectives of this review.

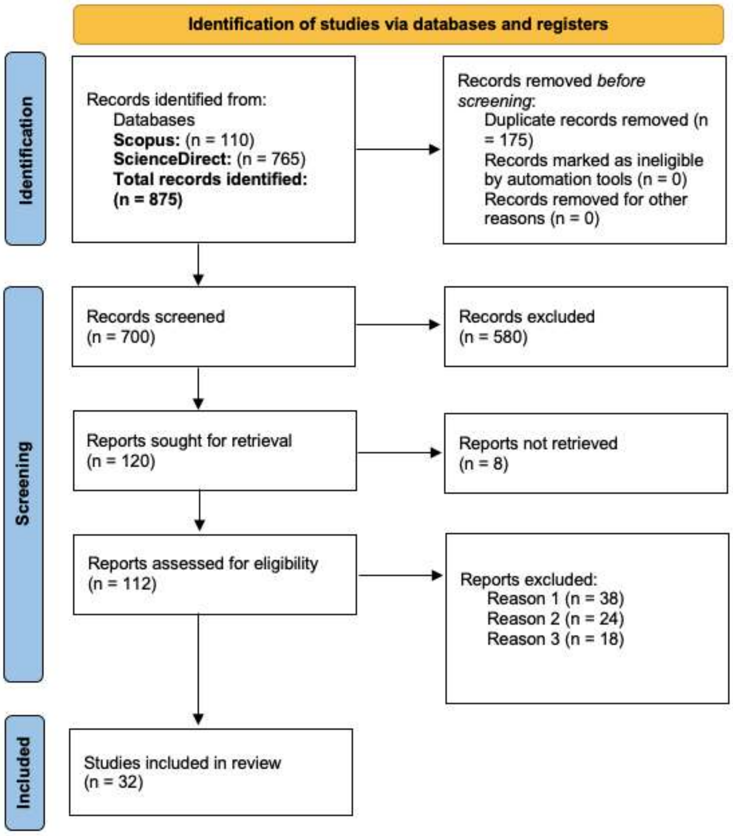

Figure 1. PRISMA flow diagram illustrating the selection process of studies related to silica enriched biochar.

As shown in Figure 1, a total of 875 records were initially identified from database searches. After removing duplicate records, 700 studies remained for title and abstract screening. During this stage, 580 records were excluded because they were not relevant to the scope of the review. Subsequently, 120 reports were sought for retrieval, of which 8 could not be accessed. A total of 112 full-text articles were then assessed for eligibility. Several studies were excluded because they were not specifically related to silica enriched biochar application, did not evaluate soil fertility or soil properties, or were categorized as review articles and other non-eligible publications. Finally, 32 studies met all inclusion criteria and were included in the systematic literature review.

2.5 Data Synthesis and Analysis

The selected studies were synthesized qualitatively by comparing the effects of silica enriched biochar application across different tropical soil orders and environmental conditions. Data extracted from each study included biochar feedstock type, pyrolysis temperature, soil order, application rate, observed changes in soil chemical and physical properties, nutrient availability, and plant response. The collected information was then grouped and analyzed based on similarities and differences in soil characteristics and biochar performance.

The analysis focused on identifying general trends regarding the influence of silica enriched biochar on soil fertility improvement, particularly soil pH, cation exchange capacity, nutrient availability, soil organic carbon, and aluminum toxicity mitigation in tropical soils. In addition, comparisons among studies were conducted to evaluate how variations in soil order and biochar characteristics affected the magnitude of soil responses. The synthesis results were interpreted descriptively to provide a comprehensive understanding of the potential role of silica enriched biochar in improving tropical soil fertility and supporting sustainable agricultural management.

3. RESULTS AND DISCUSSION

3.1 Fertility Characteristics of Contrasting Tropical Soil Orders

Tropical soil orders exhibit contrasting physicochemical characteristics and fertility constraints due to differences in weathering intensity, parent material, and environmental conditions. Highly weathered soils such as Ultisols and Oxisols are generally characterized by strong acidity, low nutrient retention, and severe phosphorus fixation, whereas younger soils such as Inceptisols and Entisols tend to exhibit more variable fertility conditions depending on their mineral composition and landscape position. These differences strongly influence nutrient dynamics and soil management strategies in tropical agroecosystems. A comparative summary of the major characteristics and fertility limitations of contrasting tropical soil orders is presented in Table III.

Table III: Comparisons of physicochemical properties and fertility constraints across major tropical soil orders.

Soil Orders	Distribution	Dominant Characteristics	Main Fertility Constraints	Dominant Mineral Composition	Implications for Soil Fertility Management	Literatures Cited
Ultisols	Humid tropics of Southeast Asia, Amazonia, and Africa	Highly weathered, acidic (<5.5), low base saturation, low CEC	Al toxicity, low P and K availability, nutrient leaching	Kaolinite with Fe/Al oxides	Liming, organic amendments, targeted P and K fertilization	[8, 43, 44]
Oxisols (Ferralsols)	Stable humid tropical regions such as Amazon and Congo basins	Extremely weathered, very acidic (<0.5), very low CEC, low OM	Severe P fixation, nutrient depletion, strong leaching	Kaolinite, gibbsite, Fe/Al sesquioxides	Intensive liming, P management, biochar and OM addition	[11, 23, 46]
Inceptisols (Cambisols)	River valleys, volcanic regions, and sloping tropical areas	Moderately developed profile, variable texture and fertility	Moderate acidity and nutrient leaching	Mixed mineralogy (kaolinite, illite, mica)	Balanced fertilization, liming if needed, erosion control	[2, 36, 54]
Entisols	Floodplains, deltas, coastal and recent deposits	Weak profile development, sandy texture, low OM and CEC	Poor nutrient and water retention, drought susceptibility	Quartz-dominated with limited clay development	Organic amendments, irrigation management, regular fertilization	[1, 53]

The comparison presented in Table 1 highlights substantial variability in fertility constraints among tropical soil orders. Highly weathered soils, particularly Ultisols and Oxisols, consistently exhibit lower nutrient availability and stronger acidity-related limitations than younger soils. Meanwhile, Inceptisols and Entisols show more variable fertility conditions, mainly influenced by parent material, texture, and degree of profile development. These contrasting characteristics indicate that the effectiveness of soil amendments may differ considerably across tropical soil orders.

3.2 Mechanistic Effects of Silica Enriched Biochar on Soil Fertility Parameters

Silica enriched biochar improves soil fertility through multiple interconnected chemical and physicochemical mechanisms that influence nutrient availability, retention, and soil buffering capacity. The effectiveness of these mechanisms is strongly associated with the alkaline nature of biochar, the presence of soluble silica, surface functional groups, and the porous carbon matrix formed during pyrolysis. In tropical soils, where nutrient leaching, phosphorus fixation, and soil acidity are major constraints, silica enriched biochar has been increasingly recognized as a promising amendment for improving key fertility parameters such as soil pH, cation exchange capacity (CEC), soil organic carbon (SOC), and macronutrient availability. A summary of the dominant mechanisms and their implications for soil fertility improvement is presented in Table IV.

Table IV: Mechanistic summary table of silica enriched biochar effects on key soil fertility parameters in tropical soils.

Soil Fertility Parameters	Mechanism of Silica Enriched Biochar	Main Soil Process Affected	Key Findings	Expected Soil Fertility Impact	Literatures Cited
pH	Release of alkaline ash and soluble silica; proton neutralization	Acidity neutralization and buffering	Si-biochar increases soil pH and buffering capacity, particularly in acidic tropical soils	Reduced acidity and Al toxicity; improved nutrient availability	[31, 43, 19]
CEC	Increased surface functional groups and negative charge sites	Nutrient retention and cation exchange	Si-biochar enhances retention of Ca^{2+}, Mg^{2+}, K^{+}, and NH_4^{+} through improved surface chemistry	Greater nutrient retention and reduced leaching	[8, 35, 42]
SOC	Addition of recalcitrant carbon and aggregate stabilization	Carbon stabilization and SOM accumulation	Phytolith-rich biochar contributes to long-term SOC storage and carbon sequestration	Improved soil structure and long-term fertility	[20, 29, 59]
Nitrogen (N)	Slow nutrient release and enhanced microbial activity	N cycling and retention	Si-biochar increases total N and reduces N leaching through microbial stimulation and adsorption processes	Improved N availability and nutrient use efficiency	[13, 37]
Phosporous (P)	Increased pH and reduced P fixation by Fe/Al oxides	P mobilization and nutrient cycling	Si-biochar enhances available P through desorption and direct nutrient contribution from ash	Increased P availability in acidic tropical soils	[13, 42, 58]
Potassium (K)	Direct K release from biochar ash and reduced leaching	K retention and release dynamics	Si-biochar acts as a slow-release K source with lower leaching losses than mineral fertilizers	Sustained K availability and improved crop nutrition	[13, 14]

The mechanisms summarized in Table IV demonstrate that silica enriched biochar can simultaneously improve multiple soil fertility parameters through both direct nutrient contributions and indirect modifications of soil chemical properties. The strongest effects are generally associated with acidity amelioration, enhanced nutrient retention, and improved phosphorus availability, which are critical constraints in highly weathered tropical soils. In addition, the porous structure and stable carbon composition of silica enriched biochar contribute to improved soil organic carbon accumulation and nutrient cycling efficiency. These findings further indicate that the dominant mechanisms and magnitude of improvement may vary depending on soil characteristics, mineral composition, and environmental conditions.

3.3 Differential Responses of Tropical Soil Orders to Silica Enriched Biochar

The effectiveness of silica enriched biochar varies considerably among tropical soil orders due to differences in mineral composition, buffering capacity, weathering intensity, and nutrient retention characteristics. Highly weathered soils generally exhibit stronger responses in soil acidity amelioration and silicon availability, whereas younger or coarse-textured soils tend to respond more prominently in nutrient retention and water-holding capacity. These contrasting responses indicate that the dominant mechanisms and fertility improvements associated with silica enriched biochar are strongly soil-specific. A comparative summary of the differential responses of tropical soil orders to silica enriched biochar application is presented in Table V.

Table V: Comparative table summarizing soil-specific responses to silica enriched biochar across major tropical soil orders.

Soil Orders	Most Responsive Parameters	Dominant Mechanism	Main Soil Fertility Improvement	Limitation or Constraint	Overall Response Trend	Literatures Cited
Oxisols (Ferralsols)	pH, CEC, SOC, N, P, K	Liming effect, carbonate dissolution, nutrient release	Available Si increased from 36 to 209 mg kg^{-1}; water retention improved up to 30%; increased biomass and CEC	Response influenced by feedstock and application rate	Consistently positive response	[29, 30, 31]

Inceptisols (Cambisols)	Water retention and microporosity	Increased micropore volume and internal porosity	Available Si increased from 55 to 97 mg kg^{-1} with moderate increases in biomass and CEC	Over-application may reduce effectiveness	Positive response under optimal application rates	[29, 31]
Ultisols	pH and Si availability	Moderate liming effect and Si release	pH buffering increased >67%; significant increases in SOC, total N, available P, and exchangeable bases reported	Higher buffering capacity limits response magnitude	Moderately positive response	[8, 48]
Entisols	N, P, K, water retention	Improved porosity and slow nutrient release	Soil P, N, and K increased by ~72%, 52%, and 33%, respectively; water retention improved by ~14%; yield increased up to 25%	Nutrient losses may still occur in sandy soils	Positive response, especially in coarse-textured soils	[12, 35]

The comparison presented in Table V demonstrates that the dominant responses to silica enriched biochar differ substantially among tropical soil orders. Highly weathered soils such as Ultisols and Oxisols generally show stronger improvements in soil acidity, silicon availability, and nutrient retention, whereas younger soils such as Entisols respond more prominently in water retention and nutrient availability. In addition, the magnitude of response appears to be influenced by factors such as soil buffering capacity, texture, and initial fertility status. Overall, these findings indicate that the agronomic effectiveness of silica enriched biochar is highly dependent on soil-specific characteristics and environmental conditions.

3.4 Implications for Tropical Soil Fertility and Crop Productivity

The improvement of soil chemical properties following silica enriched biochar application has important implications for crop productivity in tropical agroecosystems. Enhanced nutrient retention, increased silicon availability, improved cation exchange capacity, and better water-holding capacity collectively contribute to greater nutrient uptake efficiency and plant growth performance. However, crop responses vary depending on soil order, crop type, and the dominant fertility constraints of the target soil. In highly weathered tropical soils, silica enriched biochar is often associated with stronger improvements in nutrient availability and stress tolerance, whereas in coarse-textured soils its effects are more closely related to enhanced nutrient retention and water availability. A summary of the agronomic implications of silica enriched biochar application across different tropical soil orders is presented in Table VI.

Table VI: Summary table of studies on silica enriched biochar impacts on tropical soil fertility and crop productivity.

Crop Types	**Soil Orders**	**Major Soil Fertility Improvement**	**Plant or Crop Response**	**Key Findings**	**Agronomic Implications**	**Literatures Cited**
Rice	Ultisols	Increased pH, nutrient retention, and available Si	Improved biomass and lodging resistance	Rice husk biochar increased biomass by up to 29% and lodging resistance by 22% through enhanced silica accumulation and stem strength	Supports sustainable rice production and improves fertilizer efficiency	[7, 24, 33]
Wheat	Inceptisols	Increased pH, CEC, and bioavailable Si	Higher Si uptake and biomass production	Phytolith-rich biochar increased available Si from 55 to 97 mg kg^{-1} and enhanced wheat growth	Improves nutrient availability in moderately weathered soils	[14, 30]
Maize	Entisols	Improved P, K, water retention, and CEC	Increased yield and nutrient uptake	Biochar application improved nutrient retention and increased maize yield by up to	Enhances productivity in coarse-textured tropical soils	[9, 41]

				93% under low-fertility sandy soils		
Soybean	Oxisols	Increased pH, porosity, and P availability	Long-term yield improvement	Acacia-derived biochar increased soybean yield by approximately 0.4 Mg ha^{-1} per season over long-term application	Promising for long-term fertility improvement in highly weathered soils	[5, 25]

The findings summarized in Table VI indicate that silica enriched biochar can substantially improve crop performance through enhanced nutrient availability, silicon uptake, and soil fertility status. The magnitude of agronomic response appears to differ among soil orders, with highly weathered soils generally showing stronger responses in nutrient availability and productivity improvement. In contrast, improvements observed in coarse-textured soils are more strongly associated with enhanced nutrient retention and water-holding capacity. Overall, these results demonstrate the potential of silica enriched biochar to support sustainable crop production in tropical agricultural systems.

3.5 Challenges and Future Perspectives for Tropical Agricultural System

Despite its considerable potential for improving soil fertility and crop productivity, the large-scale application of silica enriched biochar in tropical agriculture still faces several technical, economic, and environmental challenges. One of the primary constraints is the variability of biochar characteristics resulting from differences in feedstock composition and pyrolysis conditions [7, 56]. Most current studies predominantly utilize rice husk or rice straw as silica-rich feedstocks due to their high phytolith content and widespread availability in rice-producing regions [18, 24]. However, comparative evaluations involving other tropical biomass sources remain limited. Variations in silica concentration, ash content, carbon stability, porosity, and surface functional groups among feedstocks can substantially influence nutrient release dynamics, cation exchange capacity, and soil amendment effectiveness [21, 34]. The absence of standardized production protocols often leads to inconsistent agronomic performance across studies and environmental conditions.

Another important limitation is the lack of long-term field validation under diverse tropical environments. Most existing studies have been conducted under laboratory, greenhouse, or short-term pot experiment conditions, which may not fully represent the complex interactions occurring in field-scale tropical agroecosystems [7, 23]. Soil properties such as texture, mineralogy, rainfall intensity, buffering capacity, and organic matter status can strongly influence the persistence and magnitude of silica enriched biochar effects [3, 55]. Furthermore, the long-term stability of fertility improvements, nutrient release patterns, and carbon sequestration potential remain insufficiently understood, particularly under continuous cropping systems and repeated amendment applications [43, 58]. Aging processes may gradually alter biochar surface chemistry and reduce its effectiveness over time, highlighting the need for multi-year field studies across contrasting tropical soil orders [21, 23].

Economic and practical constraints also remain major barriers to widespread adoption, particularly in developing tropical regions dominated by smallholder farming systems. Biochar production often requires substantial energy input, specialized pyrolysis equipment, and stable biomass supply chains, which may increase production costs and limit scalability [6, 57]. In many tropical areas, limited infrastructure and technological accessibility further constrain large-scale implementation. In addition, economic feasibility analyses assessing cost-benefit relationships, farmer adoption potential, and long-term profitability are still scarce. These limitations indicate that future development should prioritize low-cost and locally adaptable production systems integrated with agricultural waste management and circular bioeconomy approaches [7, 24, 57].

The effectiveness of silica enriched biochar is also highly dependent on soil-specific conditions, emphasizing the importance of site-specific management strategies. Highly weathered soils such as Ultisols and Oxisols may respond more strongly through improvements in pH buffering, phosphorus availability, and silicon supply, whereas coarse-textured soils such as Entisols may benefit more from enhanced water retention and nutrient-holding capacity [4, 23, 34]. Such variability demonstrates that uniform application strategies are unlikely to produce optimal results across contrasting tropical soils. Future research should therefore focus on developing tailored biochar formulations based on local soil constraints, feedstock characteristics, and crop requirements. Greater attention should also be directed toward integrating silica enriched biochar with mineral fertilizers or organic amendments to optimize nutrient use efficiency and long-term soil fertility management [49].

In addition to agronomic considerations, environmental and ecological risks associated with silica enriched biochar application require further evaluation. Potential contamination from heavy metals or toxic compounds originating from unsuitable feedstocks remains a concern, particularly when industrial or municipal biomass residues are utilized [6, 58]. Limited information is also available regarding the long-term effects of silica enriched biochar on soil biodiversity, microbial community dynamics, and ecosystem functioning under tropical conditions. Therefore, comprehensive environmental risk assessments and standardized quality control guidelines are necessary to ensure the safe and sustainable implementation of silica enriched biochar technologies [7, 30]. Overall, although silica enriched biochar demonstrates substantial promise for improving tropical soil fertility, future studies should prioritize long-term field validation, economic feasibility, environmental safety, and soil-specific management approaches to support its broader adoption in sustainable tropical agriculture [7, 39, 59].

4. DISCUSSION

The findings of this systematic review demonstrate that silica enriched biochar exerts differential effects on tropical soil orders due to variations in mineralogical composition, weathering intensity, buffering capacity, and inherent fertility status. Highly weathered soils such as Ultisols and Oxisols generally exhibited the strongest responses in terms of soil acidity amelioration, phosphorus availability, and silicon release, whereas younger soils such as Entisols and Inceptisols showed comparatively greater improvements in nutrient retention, water-holding capacity, and soil structural properties. These contrasting responses indicate that the agronomic effectiveness of silica enriched biochar is strongly governed by soil-specific physicochemical characteristics rather than by a single universal mechanism.

The substantial response observed in highly weathered tropical soils is closely associated with the dominant fertility constraints commonly found in Ultisols and Oxisols, including low pH, high exchangeable Al, low cation exchange capacity, and severe phosphorus fixation caused by abundant Fe and Al oxides. The alkaline ash fraction and soluble silica released from silica enriched biochar contribute directly to soil acidity neutralization through proton consumption, carbonate dissolution, and increased base saturation. Several studies included in this review consistently reported significant increases in soil pH and buffering capacity following biochar application, particularly in strongly acidic soils. In addition, dissolved silicate ions may compete with phosphate for adsorption sites on sesquioxide surfaces, thereby reducing phosphorus fixation and increasing P availability for plant uptake. This mechanism is especially important in tropical Oxisols where P deficiency represents one of the primary limitations to crop productivity. Similar findings have also been reported by previous studies emphasizing the role of silicon amendments in mitigating phosphorus sorption and Al toxicity in highly weathered tropical soils.

Besides improving soil acidity and phosphorus dynamics, silica enriched biochar also contributes to enhanced nutrient retention and cation exchange capacity through the development of negatively charged surface functional groups and increased porous surface area. The oxidation of biochar surfaces during aging may further increase the abundance of carboxyl and phenolic functional groups that facilitate nutrient adsorption and cation exchange processes. These effects are particularly beneficial in tropical soils characterized by intensive rainfall and nutrient leaching. In coarse-textured Entisols, the porous carbon matrix of biochar appears to function primarily as a physical reservoir for water and nutrients, explaining the substantial increases in water retention, nitrogen availability, and crop productivity observed in several studies. Improvements in soil organic carbon accumulation were also frequently reported, indicating that silica enriched biochar may contribute to long-term carbon stabilization and improved soil structural resilience in degraded tropical soils.

The findings synthesized in this review are generally consistent with previous studies demonstrating the positive effects of biochar on soil fertility and crop productivity in tropical environments. However, the magnitude and consistency of responses varied considerably among studies due to differences in feedstock type, pyrolysis temperature, application rate, climatic conditions, and soil properties. Rice husk-derived biochar, for example, often produced stronger effects on silicon availability and pH improvement because of its high phytolith and ash content, whereas woody biochars tended to exhibit lower nutrient contribution but greater carbon stability. Similarly, stronger responses were commonly observed in highly weathered soils with low buffering capacity compared with soils possessing higher clay activity or greater native fertility. These variations explain why some studies reported substantial increases in nutrient availability and crop yield, while others observed only moderate or short-term improvements.

From an agronomic perspective, the results of this review highlight the strong potential of silica enriched biochar to support sustainable soil fertility management in tropical agricultural systems. The combined benefits of acidity amelioration, enhanced nutrient retention, improved silicon supply, and increased soil organic carbon may help reduce fertilizer dependency and improve nutrient use efficiency under highly weathered tropical conditions. Furthermore, the utilization of agricultural residues such as rice husk, rice straw, or other silica-rich biomass as feedstock aligns closely with circular agriculture and waste valorization principles. Such an approach may provide dual environmental benefits through both soil restoration and agricultural waste management. The positive effects of silica enriched biochar on drought tolerance, nutrient cycling, and long-term productivity also suggest its potential contribution to climate-resilient agricultural systems in tropical regions increasingly affected by land degradation and climate variability.

Despite these promising findings, several important limitations remain within the current body of literature. Most studies included in this review were conducted under short-term greenhouse or pot experimental conditions, limiting the understanding of long-term field-scale responses under complex tropical environments. Comparative studies directly evaluating multiple soil orders under identical experimental conditions are still relatively scarce, making mechanistic interpretation more difficult. In addition, inconsistencies in biochar production methods, feedstock composition, and application rates complicate cross-study comparisons and reduce the ability to establish generalized recommendations. Economic feasibility, scalability of production systems, and potential environmental risks associated with unsuitable feedstocks also remain insufficiently evaluated, particularly for smallholder farming systems in developing tropical regions.

Future research should therefore prioritize long-term field experiments across contrasting tropical soil orders to better evaluate the persistence and stability of silica enriched biochar effects under realistic agricultural conditions. Greater attention is also needed toward developing soil-specific and crop-specific biochar formulations based on local fertility constraints, mineralogical characteristics, and climatic conditions. Furthermore, integrated approaches combining silica enriched biochar with mineral fertilizers, organic amendments, or microbial inoculants may provide synergistic benefits for nutrient use efficiency and soil restoration. Additional studies investigating biochar aging processes, microbial interactions, greenhouse gas emissions, and economic feasibility will also be essential for supporting the broader adoption of silica enriched biochar as a sustainable soil management strategy in tropical agriculture.

5. CONCLUSION

This systematic review demonstrates that silica-enriched biochar improves soil fertility through soil-specific mechanisms governed by mineralogy, weathering intensity, and buffering capacity across tropical soil orders. Highly weathered soils such as Ultisols and Oxisols responded mainly through acidity amelioration, enhanced silicon availability, and phosphorus mobilization, while younger soils such as Entisols and Inceptisols showed stronger improvements in nutrient retention, water-holding capacity, and soil structural stability. The reviewed studies consistently reported increases in soil pH, nutrient availability, cation exchange capacity, and crop productivity following silica-enriched biochar application. These findings confirm the strong potential of silica-enriched biochar as a sustainable amendment for tropical agricultural systems while emphasizing the need for soil-specific management strategies rather than uniform application approaches. Future studies should focus on long-term field validation, standardized biochar production, and integrated fertility management to optimize agronomic and environmental benefits.

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