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Assessing Silica-Enriched Biochar and N, P, K Fertilization in Newly Flooded Inceptisols: Impacts on Soil Chemical Properties, Phosphorus Use Efficiency, and Rice Productivity

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ABSTRACT

Phosphorus (P) limitation remains a major constraint to rice productivity in newly flooded Inceptisols, despite relatively high total P reserves. The conversion of mineral soils into paddy fields induces rapid changes in redox conditions, iron dynamics, and silica availability, which strongly influence P availability and fertilizer efficiency. In recent years, silica-enriched biochar has emerged as a promising soil amendment due to its capacity to improve soil chemical properties, regulate iron-mediated P fixation, and enhance nutrient retention in flooded soils. This narrative review synthesizes recent advances on the roles of silica-enriched biochar and N, P, K fertilization in modifying soil chemical properties, phosphorus use efficiency, and rice productivity in newly flooded Inceptisols. The review highlights the effects of these management strategies on soil pH, cation exchange capacity, available and potential P pools, silica dynamics, plant P and Si uptake, and yield components such as grain yield and 1000-grain weight. Evidence from recent studies indicates that silica-enriched biochar contributes to improved P availability through competitive sorption with phosphate on iron oxides and increased cation retention, while balanced N, P, K fertilization enhances nutrient uptake and yield performance. Synergistic effects between biochar-silica and mineral fertilization are particularly important during the early stages of soil flooding, when nutrient dynamics are highly unstable. This review underscores the potential of integrating silica-enriched biochar with optimized N, P, K fertilization as a sustainable strategy to improve phosphorus use efficiency and rice productivity in newly established paddy soils.

KEYWORDS: cation exchange capacity, iron–phosphorus interactions, phosphorus dynamics, rice yield components, silicon availability

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1. INTRODUCTION

1.1 Background and Significance

Rice (Oryza sativa L.) remains the primary staple food for more than half of the world's population, positioning sustainable rice production as a central pillar of global food security, particularly in developing and emerging economies [1, 2]. To meet increasing demand, rice-based agroecosystems have historically relied on intensive applications of mineral fertilizers, especially nitrogen (N), phosphorus (P), and potassium (K), to sustain yield growth [2, 4]. However, mounting evidence indicates that continued intensification of conventional fertilization has resulted in diminishing yield returns due to declining soil quality, low nutrient use efficiency, and increasing environmental externalities, including nutrient losses, eutrophication, and greenhouse gas emissions [2, 3, 4]. These challenges are particularly pronounced in transitional rice systems established on newly flooded soils, where soil chemical processes remain unstable during the initial phases of inundation [5].

In Indonesia and other tropical regions, future expansion of rice cultivation increasingly depends on marginal and transitional lands, notably Inceptisols, which occupy extensive land areas but frequently exhibit chemical constraints that limit nutrient availability and crop productivity under intensive rice-based systems [1, 2]. Inceptisols are typically characterized by weak horizon development, acidic soil reactions, low to moderate organic matter content, and unbalanced macronutrient availability, conditions that restrict their agronomic potential without targeted soil management interventions [6, 7]. When these soils are newly converted into flooded paddy systems, prolonged inundation induces rapid shifts in soil redox potential that fundamentally alter biogeochemical processes controlling iron (Fe) transformation, phosphorus mobilization, and overall nutrient dynamics [5, 8].

Under flooded conditions, the reductive dissolution of Fe(III) oxides leads to increased Fe^{2+} concentrations in the soil solution, triggering dynamic phosphorus sorption–desorption processes that govern P availability to rice plants [5, 8]. Although reductive Fe dissolution may temporarily release sorbed phosphate, newly flooded soils often experience unstable P dynamics due to re-precipitation, re-sorption, or complexation with dissolved Fe and organic matter, resulting in persistently low plant-available P despite substantial total soil P reserves [8, 10]. These processes are especially critical during the early flooding phase, when fluctuating redox conditions promote rapid Fe cycling and reduce the effectiveness of conventional P fertilization strategies [10, 11].

Phosphorus is an essential macronutrient regulating rice growth, energy transfer via adenosine triphosphate (ATP), and grain formation; however, its use efficiency in flooded Inceptisols is frequently constrained by strong soil chemical controls [8, 9]. A large proportion of soil P is immobilized through strong sorption to Fe oxides and stabilization within organic P fractions, processes that collectively limit P mobility and restrict plant uptake under anaerobic paddy conditions [8, 10]. Consequently, improving phosphorus availability and phosphorus use efficiency remains a major challenge in the sustainable management of newly flooded paddy soils.

Recent research has increasingly highlighted the pivotal role of silicon (Si) in regulating nutrient dynamics and crop performance in paddy soils [12, 13]. Rice is a strong silicon accumulator, capable of incorporating Si at levels approaching 10% of shoot dry weight, and adequate Si supply has been shown to enhance culm strength, lodging resistance, and tolerance to abiotic stresses such as drought and salinity, while also contributing to balanced nutrient uptake and utilization [14, 15, 16]. From a soil chemical perspective, monosilicic acid [$Si(OH)_4$] competes with phosphate anions for sorption sites on Fe oxides and oxyhydroxides, including goethite and ferrihydrite, which dominate P retention in many mineral soils [17, 18]. This competitive sorption mechanism can displace adsorbed phosphate into the soil solution, thereby enhancing P mobility and availability for plant uptake, particularly under flooded conditions where Fe-mediated P fixation governs nutrient dynamics [8].

In parallel, biochar derived from rice residues has emerged as a promising soil amendment for flooded agroecosystems due to its high surface area, abundant functional groups, and resistance to biological degradation [20, 21]. Biochar application has been shown to elevate soil pH through liming effects, enhance cation exchange capacity (CEC), improve nutrient retention, and stabilize soil chemical processes under anaerobic conditions, thereby contributing to improved soil fertility and nutrient cycling in paddy systems [19, 21]. When enriched with silica, biochar offers a dual functionality by simultaneously supplying plant-available Si and modifying soil chemical environments that regulate nutrient interactions [22]. Silica-enriched biochar has been reported to enhance P availability through Si–P competitive sorption on Fe oxides while reducing nutrient losses in flooded soils, indicating its potential to improve nutrient use efficiency during early flooding stages [18, 23].

Despite growing evidence supporting the individual benefits of biochar and silicon amendments, their combined interactions with conventional N, P, and K fertilization in newly flooded Inceptisols remain poorly synthesized [24]. Most existing studies emphasize pot experiments or long-established paddy soils, whereas field-scale conditions in newly converted paddy systems exhibit distinct redox-driven chemical dynamics, nutrient transformation pathways, and management constraints that limit the direct transferability of existing findings [25]. As a result, a critical knowledge gap persists regarding how silica-enriched biochar and mineral fertilization jointly regulate soil chemical properties, phosphorus use efficiency, and rice productivity during the early flooding phase of Inceptisol-based paddy systems.

Accordingly, this narrative review synthesizes recent open-access evidence on the effects of silica-enriched biochar and N, P, K fertilization on soil pH, cation exchange capacity, iron-phosphorus-silica interactions, nutrient uptake, phosphorus use efficiency, and rice yield formation in newly flooded Inceptisols. By integrating mechanistic insights across studies, this review aims to clarify key processes, management implications, and priority research gaps relevant to sustainable rice production in transitional paddy soils.

2. MATERIALS AND METHODS

2.1 Study Design and Approach

This study was conducted as a narrative review focusing on the synthesis of recent scientific literature related to the effects of silica-enriched biochar and N, P, K fertilization on soil chemical properties, phosphorus dynamics, and rice productivity in newly flooded

Inceptisols. The review adopted a conceptual synthesis approach, in which published findings were integrated and interpreted based on soil chemical mechanisms, nutrient interactions, and crop response frameworks relevant to flooded rice systems. The analytical framework was strongly aligned with the conceptual model developed in the associated thesis, emphasizing iron-mediated phosphorus dynamics, silicon-phosphorus interactions, and nutrient use efficiency under transitional flooding conditions.

2.2 Literature Sources and Selection Criteria

Peer-reviewed journal articles were collected from international scientific databases, including Google Scholar, Scopus-indexed journals, and open-access publishers such as MDPI, Frontiers, Springer Open, Elsevier Open Access, and IOP Publishing. Literature selection focused on studies published between 2016 and 2026 to ensure relevance to current soil management practices and recent methodological developments. Earlier foundational studies were included selectively when required to explain fundamental soil chemical mechanisms.

The inclusion criteria comprised studies that (i) investigated paddy soils or flooded soil systems, (ii) evaluated biochar, silicon, or their combined application, (iii) reported interactions with mineral N, P, or K fertilization, and (iv) assessed soil chemical properties, nutrient dynamics, or rice yield components. Studies conducted exclusively on upland crops, non-flooded systems, or non-soil-based experiments were excluded.

2.3 Data Collection and Extraction

Relevant information was extracted systematically from selected publications, including soil type, flooding condition, amendment characteristics (biochar source, silicon form, and application rate), fertilization regime, observed soil chemical responses (pH, cation exchange capacity, phosphorus and silicon availability), plant nutrient uptake, and rice yield components. Particular attention was given to studies explicitly describing redox processes, iron–phosphorus interactions, and silicon-mediated nutrient mobilization in flooded soils. Extracted data were organized thematically according to soil properties, nutrient dynamics, and plant response variables.

2.4 Data Analysis and Synthesis

Data analysis was conducted qualitatively through thematic synthesis rather than quantitative meta-analysis. Findings from individual studies were compared and interpreted based on consistency of observed trends, underlying soil chemical mechanisms, and agronomic relevance. Emphasis was placed on identifying mechanistic linkages among biochar-silica application, phosphorus mobilization, nutrient retention, and rice yield formation. Where applicable, reported percentage changes and relative treatment effects were discussed descriptively without recalculating statistical values. The synthesis prioritized mechanistic coherence and relevance to newly flooded Inceptisols rather than numerical aggregation.

3. RESULTS

3.1 Soil Chemical Constraints in Newly Flooded Inceptisols

Newly flooded Inceptisols constitute a transitional soil environment in which rapid shifts in redox potential significantly influence the dynamics of soil nutrients, particularly phosphorus (P) and iron (Fe). Upon inundation, the decline in soil redox potential triggers the reductive dissolution of Fe(III) oxides, thereby increasing Fe^{2+} concentrations in the soil solution and altering P mobility [26]. Under these strongly reducing conditions, Fe–P complexes may initially release some P; however, much of this liberated P is subsequently re-fixed or adsorbed onto remaining Fe and Al mineral surfaces, limiting its plant availability despite the presence of substantial total soil P reserves [28].

The predominance of Fe oxyhydroxides in highly weathered tropical soils, such as many Inceptisols, further enhances this fixation process because P exhibits high affinity for sorption to Fe (hydr)oxides under fluctuating redox conditions [11]. Consequently, even though flooding can transiently elevate P solubility via reductive processes, available P often remains low because dissolved P becomes re-adsorbed or precipitated as secondary mineral phases shortly after redox transitions [28].

Inceptisols typically exhibit inherently low soil pH, low cation exchange capacity (CEC), and reduced organic matter content, which together exacerbate nutrient limitation by promoting stronger fixation of P by iron and aluminium compounds and diminishing the soil's buffering capacity [2]. Acidic reactions in these soils increase the activity of Al and Fe ions, which further enhances P sorption and immobilization, making conventional mineral fertilization alone insufficient to improve P availability effectively [2].

Low organic matter content also constrains microbial energy sources necessary for effective redox transformations and nutrient mobilization. Organic carbon serves as an electron donor in microbial processes that influence Fe cycling; limited labile organic matter therefore restricts the microbial reduction of Fe(III) and reduces the potential release of associated P, limiting the contribution of native soil P to rice uptake [28].

In such chemically constrained environments, repeated high rates of mineral P fertilization may not proportionally increase plant-available P and can even worsen soil chemical imbalance by lowering pH and promoting further Al and Fe activity, which reinforces P fixation [27]. Therefore, nutrient limitation in newly flooded Inceptisols should be understood not merely as insufficient fertilization input, but as a consequence of unfavorable soil chemical properties, particularly redox-driven Fe and Al dynamics, acidity, and low organic matter, that constrain nutrient retention and availability.

These constraints indicate the necessity of soil amendments that can alter soil pH, increase CEC, and reduce excessive metal activity to improve fertilizer efficiency in early paddy soil development. By buffering acidity and modifying the soil chemical environment, such amendments can help decrease P fixation and improve the temporal availability of nutrients under dynamic flooded conditions.

3.2 Role of Silica-Enriched Biochar in Regulating Soil Chemical Properties

Silica-enriched biochar acts as a multifunctional soil amendment capable of simultaneously addressing several key chemical constraints commonly encountered in newly flooded Inceptisols [22]. One of the primary mechanisms through which biochar exerts its influence is the regulation of soil pH, as most biochars derived from crop residues exhibit an alkaline character due to the presence of base cations such as Ca^{2+}, Mg^{2+}, and K^{+} that are released following soil application [19, 21]. In acidic Inceptisols, particularly those newly subjected to flooding, this liming effect is critical for buffering rapid pH declines associated with redox-driven proton consumption and release processes [8].

An increase in soil pH following biochar application has direct implications for iron (Fe) chemistry under flooded conditions, as higher pH values promote the precipitation of Fe as poorly crystalline hydroxides rather than remaining in soluble or highly reactive forms [5, 8]. By suppressing excessive Fe solubility and moderating the reduction of Fe(III) to Fe^{2+}, silica-enriched biochar indirectly limits Fe-mediated phosphorus fixation, a dominant constraint in newly flooded paddy soils [8, 10]. This stabilization of Fe dynamics is particularly important during the early flooding phase, when rapid shifts in redox potential can otherwise lead to unstable phosphorus availability and inefficient fertilizer use [8, 11].

Beyond pH regulation, the physicochemical properties of biochar, namely its high specific surface area and abundance of oxygen-containing functional groups, play a central role in enhancing soil cation exchange capacity (CEC) [20, 21]. In newly flooded Inceptisols, which are often characterized by low organic matter content and weak structural development, this biochar-induced increase in CEC represents a key mechanism for improving soil chemical resilience and nutrient retention [7, 19]. Enhanced CEC enables the soil to more effectively retain nutrient cations supplied through N, P, and K fertilization, thereby reducing leaching and diffusion losses under flooded conditions and stabilizing nutrient availability throughout the rice growth cycle [19, 25].

The enrichment of biochar with silica further strengthens its regulatory function by introducing an additional mechanism that directly influences phosphorus dynamics in Fe-dominated paddy soils [22]. Silicon supplied in the form of monosilicic acid can compete with phosphate for sorption sites on Fe oxides and oxyhydroxides, a process that is enhanced when biochar surfaces provide additional reactive interfaces for sorption–desorption reactions [17, 18]. This competitive sorption mechanism facilitates the desorption of previously fixed phosphate into the soil solution, increasing P mobility and availability to rice roots, particularly under anaerobic conditions where Fe cycling dominates nutrient transformations [8, 18].

Moreover, the combined presence of biochar and silica contributes to the stabilization of soil chemical processes by buffering fluctuations in pH, redox potential, and nutrient concentrations that are typical of newly flooded systems [22]. By moderating extreme chemical shifts during early flooding, silica-enriched biochar creates a more favorable rhizosphere environment that supports sustained nutrient uptake and reduces the risk of nutrient antagonism or toxicity associated with excessive Fe and Al activity [8, 19]. This stabilization function is particularly relevant in transitional paddy soils, where management interventions must compensate for the lack of long-term soil structural and biochemical equilibrium.

Collectively, these mechanisms indicate that silica-enriched biochar does not merely act as a passive soil conditioner but rather functions as an active regulator of soil chemical processes in newly flooded Inceptisols [22]. Its capacity to integrate pH buffering, CEC enhancement, Fe–P interaction modulation, and silicon supply underscores its potential role as a strategic amendment for improving nutrient efficiency and soil chemical stability in transitional rice production systems [8, 19].

3.3 Silicon–Phosphorus–Iron Interactions and Phosphorus Mobilization

Silicon exerts a significant regulatory function in phosphorus (P) dynamics of flooded soils by altering surface chemical interactions among phosphate ions, iron (Fe) oxides, and soil colloids, thereby influencing P mobility and bioavailability [10]. In anaerobic conditions typical of flooded paddy soils, Fe(III) oxides that strongly adsorb phosphate undergo partial reductive dissolution to Fe(II), which can release previously immobilized phosphate into the soil solution [29]. However, in newly flooded Inceptisols, Fe-mediated phosphorus fixation often remains dominant during early flooding stages due to incomplete reductive dissolution and the persistence of reactive Fe hydroxides [31].

Silicic acid (H_4SiO_4) competes directly with phosphate ions for adsorption sites on Fe and Al oxides through ligand exchange mechanisms, thereby weakening Fe–P bonding and enhancing P desorption into the soil solution [10]. This competitive sorption process is particularly effective under acidic to slightly acidic soil conditions, where Fe oxides exhibit high surface reactivity toward both silicate and phosphate anions; the consequent competition between dissolved silicic acid and phosphate for sorption sites on Fe mineral surfaces can mobilize previously adsorbed P, shifting it into more labile, plant-available pools without necessarily altering total soil P content [18]. Under flooded conditions, silicon-induced suppression of phosphate fixation is further reinforced by Si-mediated modifications of Fe mineralogy, including the transformation of Fe(III) oxides into less reactive forms with lower P sorption capacity during prolonged submergence [8, 18]. Silicon amendments thus contribute to sustained phosphorus availability throughout the cropping period rather than inducing a short-term release pulse.

When supplied via silica-enriched biochar, silicon is released gradually into the soil solution through slow dissolution of silicate minerals embedded within the biochar matrix [22]. This controlled release from silica-enriched biochar into the soil solution can sustain prolonged interaction between dissolved silicate and phosphate ions at mineral surfaces, effectively maintaining elevated concentrations of plant-available phosphorus throughout extended periods of crop growth due to continuous competitive desorption of phosphate from soil sorption sites and slow dissolution kinetics of biochar-derived silicate [18, 33]. Compared with soluble silicon fertilizers, silica-enriched biochar provides a more stable silicon source that minimizes rapid leaching losses under flooded soil conditions [22].

The porous structure and high surface area of biochar further enhance phosphorus mobilization by adsorbing Fe^{2+} ions released during reductive dissolution, thereby limiting secondary Fe–P precipitation reactions [32]. Additionally, biochar surfaces can act as temporary sinks for phosphate, facilitating reversible adsorption–desorption processes that buffer soil solution P concentrations [10, 33]. This buffering capacity improves synchronization between phosphorus release and plant uptake, ultimately enhancing phosphorus use efficiency (PUE) in low-input rice production systems [34].

From a nutrient management perspective, enhancing soil phosphorus availability through amendments that increase silicon availability, such as silica-enriched biochar, can contribute to sustainable nutrient strategies that improve phosphorus availability for crops. Increased silicon availability has been shown to mobilize phosphorus in paddy soils by competing with phosphate for binding sites on iron (Fe) mineral surfaces, thereby raising soil solution P concentrations and plant-available P [8]. Additionally, silicon amendments have been observed to increase extractable phosphorus in soils by modifying soil chemical properties, supporting the conceptual basis for Si-mediated enhancement of P availability [30]. This approach is particularly relevant for intensively cultivated flooded soils, where repeated P fertilization leads to long-term accumulation of Fe-bound phosphorus with low agronomic efficiency [10]. Therefore, integrating silicon-rich biochar into flooded soil management frameworks offers a synergistic pathway to improve soil chemical fertility, enhance phosphorus cycling, and support environmentally efficient crop production systems [22].

3.4 Interaction with N, P, K Fertilization, Nutrient Use Efficiency, and Rice Yield

Balanced nitrogen (N), phosphorus (P), and potassium (K) fertilization remains essential to support rice growth and yield; however, the efficiency of mineral fertilizer use is strongly conditioned by soil chemical properties and nutrient retention mechanisms in soil. Meta-analysis and review evidence indicate that biochar application consistently enhances soil nutrient availability and increases cation exchange capacity (CEC), which improves the retention and cycling of nutrient cations such as NH_4^+, K^+, and Ca^{2+}, thereby reducing nutrient leaching losses and bolstering fertilizer responsiveness [35, 36]. In newly flooded Inceptisols, silica-enriched biochar modifies the soil chemical environment to enhance the effectiveness of mineral fertilizers rather than replacing them entirely. Its inherently high surface area and abundance of negatively charged functional groups increase soil cation exchange capacity (CEC), thereby improving the retention of fertilizer-derived cations such as NH_4^+, K^+, and Ca^{2+} and reducing their susceptibility to leaching losses [38, 39]. Global synthesis further confirms that biochar-induced improvements in soil physicochemical properties, including CEC and nutrient buffering capacity, contribute to more stable nutrient availability across cropping systems, supporting higher fertilizer use efficiency under intensive management scenarios [37].

In parallel, the liming effect of biochar can mitigate excessive iron (Fe) activity in acidic paddy soils by increasing soil pH and altering redox-sensitive chemical conditions that otherwise favor Fe-induced phosphorus fixation. Evidence from flooded soil systems indicates that biochar application modifies the temporal dynamics and vertical distribution of Fe and phosphorus (P) under submergence, resulting in higher concentrations of plant-available P during critical stages of crop growth [29]. In acidic soils, rice straw–derived biochar has further been shown to enhance phosphorus availability and P cycling by suppressing strong Fe-P interactions, thereby allowing a greater proportion of applied P to remain in bioavailable forms for extended periods compared with unamended soils [40].

Furthermore, co-application of biochar with mineral fertilizers has been consistently reported to enhance soil nutrient availability relative to sole fertilization. Biochar improves soil chemical properties such as nutrient retention capacity and cation exchange capacity, which reduces nutrient losses and promotes more efficient nutrient uptake by crops. Experimental evidence demonstrates that combined biochar–fertilizer application increases nitrogen retention in soil and improves plant N uptake, indicating broader benefits for nutrient use efficiency when biochar is integrated with conventional fertilization strategies [41]. Similar synergistic effects have been observed for overall nutrient availability and biomass production under mineral fertilization regimes, supporting the role of biochar as a complementary amendment that enhances fertilizer effectiveness through sustained improvements in soil chemical conditions [42].

The interaction between silica-enriched biochar and balanced N, P, and K fertilization can conceptually promote synchronization between nutrient release and plant demand throughout the rice growth cycle. Biochar-induced improvements in nutrient retention and buffering capacity support more sustained availability of nitrogen and phosphorus during early vegetative stages, which enhances tillering, root expansion, and early biomass accumulation by reducing nutrient losses and improving plant nutrient uptake efficiency [45, 54]. As the crop progresses into reproductive development, improved retention and availability of phosphorus and potassium facilitate key physiological processes such as energy transfer, assimilate translocation, and panicle development, thereby contributing to higher grain yield and yield stability under fertilized conditions [52].

Empirical evidence further demonstrates that the combined application of biochar with chemical or organic fertilizers enhances nutrient use efficiency, including phosphorus use efficiency, by increasing plant nutrient uptake while simultaneously reducing fertilizer loss pathways such as leaching or chemical fixation in soil [45, 53, 54]. These synergistic interactions are particularly relevant in transitional paddy soils such as newly flooded Inceptisols, where strong soil chemical constraints and inefficient nutrient retention would otherwise limit fertilizer effectiveness and crop nutrient acquisition.

From a crop physiological perspective, synchronized nutrient supply throughout the rice growth cycle is critical for optimizing plant development and yield. Early vegetative availability of N, P, and K improves root traits and canopy establishment, thereby supporting higher yield potential in rice [48]. As rice transitions into reproductive and grain-filling stages, the co-supply of P and K improved root activity, nutrient uptake, and translocation to aboveground organs, which promoted panicle development and increased grain number per panicle [49].

Overall, the integration of silica-enriched biochar with balanced N, P, and K fertilization promotes higher nutrient use efficiency by aligning nutrient availability with crop demand while minimizing chemical constraints associated with iron (Fe) activity, low cation exchange capacity (CEC), and nutrient retention limitations typical of newly flooded Inceptisols. Silica-enriched biochar has been shown to improve soil chemical properties, including available phosphorus and potassium levels and CEC, when applied alongside NPK fertilizers, indicating enhanced soil fertility and nutrient supply potential [24]. Furthermore, meta-analytical evidence demonstrates that the combined application of biochar with mineral fertilizers can increase nutrient uptake and use efficiencies compared with fertilizers applied alone, particularly in soils with inherently low organic matter and high fixation capacity [50, 51]. This synergistic management strategy is therefore particularly relevant for improving fertilizer efficiency and sustainability in transitional paddy soils, where conventional fertilization often results in suboptimal nutrient utilization and environmental losses.

3.6 Conceptual Implications for Sustainable Management of Newly Flooded Inceptisols

The conceptual synthesis presented in this review emphasizes that improving rice productivity in newly flooded Inceptisols requires an integrated approach that targets soil chemical constraints at their source. Silica-enriched biochar functions as a stabilizing soil amendment that modifies soil pH, enhances cation exchange capacity (CEC), and influences iron (Fe) dynamics, thereby facilitating phosphorus mobilization and improving overall nutrient availability [8, 18, 49]. When combined with optimized N, P, and K fertilization, this amendment strategy promotes higher phosphorus use efficiency and improved nutrient uptake compared with sole mineral fertilizer applications, particularly in soils with low organic matter content and high P-fixing capacity [25, 44, 45].

From a sustainability perspective, such an approach offers the potential to reduce reliance on high fertilizer inputs while maintaining soil health and productivity by aligning nutrient availability with crop demand and mitigating chemical constraints related to Fe–P interactions and low CEC [25, 33]. This conceptual framework thus provides a robust foundation for future field-scale evaluations and supports the development of adaptive nutrient management strategies tailored to transitional paddy soils, where conventional fertilization alone often fails to achieve efficient nutrient use and stable yield formation.

4. DISCUSSION

This review identifies that the productivity of newly flooded Inceptisols is primarily limited by inherent chemical constraints, specifically soil acidity, low cation exchange capacity (CEC), and strong phosphorus fixation driven by iron and aluminum dynamics during redox transitions. Silica-enriched biochar emerges from this synthesis as a strategic, multifunctional amendment capable of overcoming these barriers. unlike standard fertilization which often leads to nutrient immobilization, this amendment actively regulates the soil chemical environment through three synergistic mechanisms.

First, the alkaline properties of biochar provide a critical buffering capacity that neutralizes acidity and precipitates excessive soluble iron, thereby stabilizing the rhizosphere against rapid pH fluctuations typical of early flooding. Second, the porous structure of the biochar significantly increases CEC, creating a reservoir that retains fertilizer-derived cations like ammonium and potassium, preventing them from leaching. Third, and most notably, the slow release of monosilicic acid from the amendment drives a competitive desorption process. Silicate ions displace phosphate ions from binding sites on iron oxides, effectively "unlocking" fixed phosphorus and maintaining its availability in the soil solution for plant uptake.

These mechanisms have profound implications for nutrient management. The integration of silica-enriched biochar with balanced NPK fertilization transforms the soil system from a nutrient-fixing environment to one of efficient nutrient cycling. By synchronizing nutrient availability with crop demand, supporting root development in vegetative stages and energy transfer during reproduction, this approach enhances overall nutrient use efficiency. Consequently, this suggests that mineral fertilizer inputs could be reduced without compromising yields, addressing both economic and environmental concerns in intensive rice production.

While this conceptual framework is robust, future research must transition from theoretical and pot-scale findings to long-term field trials. Validating the optimal ratios of biochar to silica and assessing the economic feasibility of this technology will be essential for developing scalable, sustainable management protocols for transitional paddy soils.

5. CONCLUSION

This review establishes that silica-enriched biochar functions as a transformative soil regulator, rather than a passive conditioner, capable of overcoming the inherent chemical constraints of newly flooded Inceptisols. The primary contribution of this synthesis is the mechanistic clarification of silicon-mediated competitive desorption, which alongside pH buffering and CEC enhancement effectively "unlocks" iron-bound phosphorus reserves that are otherwise inaccessible. Consequently, integrating this amendment with balanced fertilization offers a vital strategy to decouple rice productivity from excessive mineral inputs, thereby enhancing nutrient use efficiency in transitional soil environments. Future research must prioritize long-term field validation to optimize amendment ratios and assess the economic viability of this approach for sustainable intensification in tropical wetlands.

REFERENCES

1. FAO. (2022). The future of food and agriculture – Drivers and triggers for transformation. Food and Agriculture Organization of the United Nations, Rome. https://doi.org/10.4060/cc0959en
2. Susanti, W. I., Cholidah, S. N., & Agus, F. (2024). Agroecological nutrient management strategy for attaining sustainable rice self-sufficiency in Indonesia. Sustainability, 16(2), 845. https://doi.org/10.3390/su16020845
3. Zhang, X., Davidson, E. A., Mauzerall, D. L., Searchinger, T. D., Dumas, P., & Shen, Y. (2015). Managing nitrogen for sustainable development. Nature, 528(7580), 51–59. https://doi.org/10.1038/nature15743
4. Lal, R. (2020). Regenerative agriculture for food and climate. Journal of Soil and Water Conservation, 75(5), 123A–124A. https://doi.org/10.2489/jswc.2020.0620A
5. Kirk, G. J. D. (2004). The biogeochemistry of submerged soils. Wiley-Blackwell.
6. BBSDLP. (2020). *Peta sumber daya lahan pertanian Indonesia skala 1:250.000. Balai Besar Sumberdaya Lahan Pertanian*, Badan Litbang Pertanian, Kementerian Pertanian, Indonesia.
7. Muslim, R. Q., Kricella, P., Pratamaningsih, M. M., Purwanto, S., Suryani, E., & Ritung, S. (2020). Characteristics of Inceptisols derived from basaltic andesite from several locations in volcanic landform. Sains Tanah, 17(2), 115–121. https://doi.org/10.20961/STJSSA.V17I2.38221
8. Schaller, J., Faucherre, S., Joss, H., Obst, M., Goeckede, M., Planer-Friedrich, B., & Peiffer, S. (2022). Silicon as a potential limiting factor for phosphorus availability in paddy soils. Scientific Reports, 12, 20805. https://doi.org/10.1038/s41598-022-20805-4
9. Veneklaas, E. J., Lambers, H., Bragg, J., Finnegan, P. M., Lovelock, C. E., Plaxton, W. C., Price, C. A., Scheible, W. R., Shane, M. W., White, P. J., & Raven, J. A. (2012). Opportunities for improving phosphorus-use efficiency in crop plants. New Phytologist, 195(2), 306–320. https://doi.org/10.1111/j.1469-8137.2012.04190.x
10. Ibrahim, M., Iqbal, M., Tang, Y.-T., Khan, S., Guan, D.-X., & Li, G. (2022). Phosphorus mobilization in plant–soil environments and inspired strategies for managing phosphorus: A review. Agronomy, 12(10), 2539. https://doi.org/10.3390/agronomy12102539

11. Maranguit, D., Guillaume, T., & Kuzyakov, Y. (2017). Effects of flooding on phosphorus and iron mobilization in highly weathered soils under different land-use types: Short-term effects and mechanisms. CATENA, 158, 161–170. https://doi.org/10.1016/j.catena.2017.06.023
12. Huang, S., Pu, L., He, G., Wang, X., Chen, D., Xie, X., Qie, L., Dan, Y., Zhang, R., Gong, Z., & Lu, Y. (2024). Silicon in soil and its interaction with nitrogen, phosphorus, and potassium nutrients on rice yield: A case study of paddy fields in the Taihu Lake region, China, without a history of silicon fertilization. Soil and Tillage Research, 238, 106027. https://doi.org/10.1016/j.still.2024.106027
13. Yang, X., Ni, Y., Li, Z., Yue, K., Wang, J., Li, Z., Song, Z., & others. (2024). Silicon in paddy fields: Benefits for rice production and the potential of rice phytoliths for biogeochemical carbon sequestration. Science of the Total Environment, 172497. https://doi.org/10.1016/j.scitotenv.2024.172497
14. Irfan, M., Maqsood, M. A., Rehman, H. u., Mahboob, W., Sarwar, N., Hafeez, O. B. A., Hussain, S., Ercisli, S., Akhtar, M., & Aziz, T. (2023). Silicon Nutrition in Plants under Water-Deficit Conditions: Overview and Prospects. Water, 15(4), 739. https://doi.org/10.3390/w15040739
15. Jiang, H., Jiang, Z., Zhang, H., Li, Y., Li, W., Gao, K., Ma, X., Wang, G., Wei, X., & Wu, Z. (2025). Silicon Nutrition Improves Lodging Resistance of Rice Under Dry Cultivation. Plants, 14(3), 361. https://doi.org/10.3390/plants14030361
16. Elekhtyar, N. M., & AL-Huqail, A. A. (2023). Influence of Chemical, Organic, and Biological Silicon Fertilization on Physiological Studies of Egyptian Japonica Green Super Rice (*Oryza sativa* L.). Sustainability, 15(17), 12968. https://doi.org/10.3390/su151712968
17. Klotzbücher, T., Treptow, C., Kaiser, K. et al. Sorption competition with natural organic matter as mechanism controlling silicon mobility in soil. Sci Rep 10, 11225 (2020). https://doi.org/10.1038/s41598-020-68042-x
18. Uhuegbue, P. O., Stein, M., Kalbitz, K., & Schaller, J. (2024). Silicon effects on soil phosphorus availability: Results obtained depend on the method used. Frontiers in Environmental Science, 12, 1461477. https://doi.org/10.3389/fenvs.2024.1461477
19. Mon, W. W., Toma, Y., & Ueno, H. (2024). Residual Effects of Rice Husk Biochar and Organic Manure Application after 1 Year on Soil Chemical Properties, Rice Yield, and Greenhouse Gas Emissions from Paddy Soils. Soil Systems, 8(3), 91. https://doi.org/10.3390/soilsystems8030091
20. Novair, B. S., Cheraghi, M., Faramarzi, F., Asgari Lajayer, B., Senapathi, V., Astatkie, T., & Price, G. W. (2023). Reviewing the role of biochar in paddy soils: An agricultural and environmental perspective. Ecotoxicology and Environmental Safety, 263, 115228. https://doi.org/10.1016/j.ecoenv.2023.115228
21. Si, L., Xie, Y., Ma, Q., & Wu, L. (2018). The Short-Term Effects of Rice Straw Biochar, Nitrogen and Phosphorus Fertilizer on Rice Yield and Soil Properties in a Cold Waterlogged Paddy Field. Sustainability, 10(2), 537. https://doi.org/10.3390/su10020537
22. Sofyan, E. T., Citraresmini, A., Marganingrum, D., Mulyono, A., Djuwansah, R., Bachtiar, T., Nurjayati, R., Rachmawati, V., Hidawati, H., & Irwandhi, I. (2025). Assessment of silica-enriched biochar for enhancing soil fertility and mitigating methane emissions in acid-stressed rice fields. Journal of Ecological Engineering, 26(4), 148–160. https://doi.org/10.12911/22998993/188093
23. Schaller, J., Kleber, M., Puppe, D. et al. The importance of reactive silica for maintaining soil health. Plant Soil 513, 1651–1662 (2025). https://doi.org/10.1007/s11104-025-07299-5
24. Sofyan, E. T., Suryaningrat, I. B., & Nurida, N. L. (2025). The effect of biochar-silica and N, P, K fertilization on soil pH, silica content, phosphorus uptake, and rice yield in Inceptisols. International Journal of Life Science and Agriculture Research, 4(4), 1–12. https://doi.org/10.55677/ijlsar/V04I04Y2025-03
25. Ali, I., Yuan, P., Ullah, S., Iqbal, A., Zhao, Q., Liang, H., Khan, A., Imran, Zhang, H., Wu, X., Wei, S., Gu, M., & Jiang, L. (2022). Biochar Amendment and Nitrogen Fertilizer Contribute to the Changes in Soil Properties and Microbial Communities in a Paddy Field. Frontiers in microbiology, 13, 834751. https://doi.org/10.3389/fmicb.2022.834751
26. Grigg, A. R. C., Thomas Arrigo, L. K., Schulz, K., Rothwell, K. A., Kaegi, R., & Kretzschmar, R. (2022). Ferrihydrite transformations in flooded paddy soils: rates, pathways, and product spatial distributions. Environmental science. Processes & impacts, 24(10), 1867–1882. https://doi.org/10.1039/d2em00290f
27. Theresa, K., Vijayakumar, S., Muthukrishnan, R., & Raja, V. (2026). Soil quality index assessment for conventional, organic and INM based rice cropping systems using key indicators as influenced by imbalanced fertilization. Frontiers in Environmental Science, 13, 1698081. https://doi.org/10.3389/fenvs.2025.1698081
28. Toledo, L., R. (2022). Dynamics of P under redox conditions in rice in tropical soils. Biomedical Journal of Scientific & Technical Research, 44(1), 34889–34894. https://doi.org/10.26717/BJSTR.2022.44.006552
29. Lai, Y.-R., & Wang, S.-L. (2025). Effects of Biochar on the Temporal Dynamics and Vertical Distribution of Iron and Phosphorus Under Soil Submergence. Agronomy, 15(6), 1394. https://doi.org/10.3390/agronomy15061394

30. Greger, M., Landberg, T., & Vaculík, M. (2018). Silicon Influences Soil Availability and Accumulation of Mineral Nutrients in Various Plant Species. Plants, 7(2), 41. https://doi.org/10.3390/plants7020041
31. Li, Y., Chen, M., Liu, X., & Huo, Z. (2026). Redox-mediated Fe-P coupling modulates phosphorus releasing in paddy soils: Hydrological controls under water-saving irrigation. Journal of Contaminant Hydrology, 276, 104774. https://doi.org/10.1016/j.jconhyd.2025.104774
32. Luo, D., Wang, L., Nan, H., Cao, Y., Wang, H., Kumar, T. V., & Wang, C. (2023). Phosphorus adsorption by functionalized biochar: a review. Environmental Chemistry Letters, 21(1), 497-524. https://doi.org/10.1007/s10311-022-01519-5
33. Zhang, L., Chang, L., Liu, H., Puy Alquiza, M. de J., & Li, Y. (2025). Biochar application to soils can regulate soil phosphorus availability: A review. Biochar. Advance online publication. https://doi.org/10.1007/s42773-024-00415-1
34. Qin, S., Rong, F., Zhang, M., Su, G., Wang, W., Wu, L., Wu, A., & Chen, F. (2023). Biochar Can Partially Substitute Fertilizer for Rice Production in Acid Paddy Field in Southern China. Agronomy, 13(5), 1304. https://doi.org/10.3390/agronomy13051304
35. Nkoh, J. N., Baquy, M. A.-A., Mia, S., Shi, R., Kamran, M. A., Mehmood, K., & Xu, R. (2021). A Critical-Systematic Review of the Interactions of Biochar with Soils and the Observable Outcomes. Sustainability, 13(24), 13726. https://doi.org/10.3390/su132413726
36. Alkharabsheh, H. M., Seleiman, M. F., Battaglia, M. L., Shami, A., Jalal, R. S., Alhammad, B. A., Almutairi, K. F., & Al-Saif, A. M. (2021). Biochar and Its Broad Impacts in Soil Quality and Fertility, Nutrient Leaching and Crop Productivity: A Review. Agronomy, 11(5), 993. https://doi.org/10.3390/agronomy11050993
37. Teng, X., Huang, D., Zhi, Y., Li, Y., Dong, D., Wu, X., Wang, Y., Jiang, Z., Huang, H., Tang, Y., Liu, D., & Xu, W. (2025). Effects of biochar on soil properties as well as available and TCLP-extractable Cu contents: A global meta-analysis. Scientific Reports, 15, 32853. https://doi.org/10.1038/s41598-025-18170-z
38. Huang, W., Jia, Y., Niu, C., Zhang, H., Wang, Y., & Feng, C. (2024). Effects of carbon-based modified materials on soil water and fertilizer retention and pollution control in rice root zone. Sustainability, 16(16), 6750. https://doi.org/10.3390/su16166750
39. Xu, P., Gao, Y., Cui, Z., Wu, B., Yan, B., Wang, Y., Zaitongguli, K., Wen, M., Wang, H., Jing, N., Wang, Y., Chao, C., & Xue, W. (2023). Research progress on effects of biochar on soil environment and crop nutrient absorption and utilization. Sustainability, 15(6), 4861. https://doi.org/10.3390/su15064861
40. He, W., Zhang, J., Gao, W., Chen, Y., & Wei, Z. (2025). Enhancing phosphorus availability and dynamics in acidic soils through rice straw biochar application: A sustainable alternative to chemical fertilizers. Frontiers in Sustainable Food Systems, 9, 1506609. https://doi.org/10.3389/fsufs.2025.1506609
41. Peng, J., Han, X., Li, N., Chen, K., Yang, J., Zhan, X., Luo, P., & Liu, N. (2021). Combined application of biochar with fertilizer promotes nitrogen uptake in maize by increasing nitrogen retention in soil. Biochar, 3, 367–379. https://doi.org/10.1007/s42773-021-00090-6
42. Stopa, W., Wróbel, B., Paszkiewicz-Jasińska, A., & Strzelczyk, M. (2023). Effect of Biochar Application and Mineral Fertilization on Biomass Production and Structural Carbohydrate Content in Forage Plant Mixture. Sustainability, 15(19), 14333. https://doi.org/10.3390/su151914333
43. Keteku, A.K., Amegbor, I.K., Yeboah, S. et al. Sustaining Productivity while Reducing Methane Emission in Calcareous Soils: Implications of Combining Inorganic Fertilizer and Biochar. Int. J. Plant Prod. 19, 141–153 (2025). https://doi.org/10.1007/s42106-024-00325-z
44. An, N., Zhang, L., Liu, Y., Shen, S., Li, N., Wu, Z., Yang, J., Han, W., & Han, X. (2022). Biochar application with reduced chemical fertilizers improves soil pore structure and rice productivity. Chemosphere, 298, 134304. https://doi.org/10.1016/j.chemosphere.2022.134304
45. Glaser, B., & Lehr, V. I. (2019). Biochar effects on phosphorus availability in agricultural soils: A meta-analysis. Scientific reports, 9(1), 9338. https://doi.org/10.1038/s41598-019-45693-z
46. Jin, J., Fang, Y., He, S., Liu, Y., Liu, C., Li, F., Khan, S., Eltohamy, K. M., Liu, B., & Liang, X. (2023). Improved phosphorus availability and reduced degree of phosphorus saturation by biochar-blended organic fertilizer addition to agricultural field soils. Chemosphere, 317, 137809. https://doi.org/10.1016/j.chemosphere.2023.137809
47. Zhang, G., Li, X., Gao, S., Li, J., & Gong, C. (2025). Effects of combined application of biochar and organic fertilizer on soil improvement. In M. Jradi et al. (Eds.), Proceedings of the 2025 7th International Conference on Civil Engineering, Environment Resources and Energy Materials (CCESEM 2025), Advances in Engineering Research (Vol. 281, pp. 333–339). Atlantis Press. https://doi.org/10.2991/978-94-6463-902-5_32
48. Du, M., Zhang, W., Gao, J., Liu, M., Zhou, Y., He, D., Zhao, Y., & Liu, S. (2022). Improvement of Root Characteristics Due to Nitrogen, Phosphorus, and Potassium Interactions Increases Rice (Oryza sativa L.) Yield and Nitrogen Use Efficiency. Agronomy, 12(1), 23. https://doi.org/10.3390/agronomy12010023

49. Liu, Y., Gao, J., Zhao, Y., & others. (2024). Effects of different phosphorus and potassium supply on the root architecture, phosphorus and potassium uptake, and utilization efficiency of hydroponic rice. Scientific Reports, 14, 21178. https://doi.org/10.1038/s41598-024-72287-1
50. Ali, S., Rizwan, M., Qayyum, M. F., Ok, Y. S., Ibrahim, M., Riaz, M., Arif, M. S., Hafeez, F., Al-Wabel, M. I., & Shahzad, A. N. (2017). Biochar soil amendment on alleviation of drought and salt stress in plants: A critical review. Environmental Science and Pollution Research, 24(12), 12700–12712. https://doi.org/10.1007/s11356-017-8904-x
51. Yuan, X., Gu, X., Liang, R., Ban, G., Ma, L., He, T., & Wang, Z. (2024). Comparing combined application of biochar and nitrogen fertilizer in paddy and upland soils: Processes, enhancement strategies, and agricultural implications. Science of The Total Environment, 933, 173160. https://doi.org/10.1016/j.scitotenv.2024.173160
52. Li, Y., Wang, J., Lu, J., Feng, Y., Li, J., Guo, Z., Lin, X., & Han, Y. (2025). Effects of combined application of compound fertilizer and biochar on absorption and utilization of phosphorus by wheat. PeerJ, 13, e20308. https://doi.org/10.7717/peerj.20308
53. Ma, D., Wang, Y., Zheng, T., Zhou, Q., & Sheng, J. (2025). Synergy of biochar and organic fertilizer reduces phosphorus leaching. Agronomy, 15(11), 2528. https://doi.org/10.3390/agronomy15112528
54. Yan, B., Zhang, Y., Wang, Y., Rong, X., Peng, J., Fei, J., & Luo, G. (2023). Biochar amendments combined with organic fertilizer improve maize productivity and mitigate nutrient loss by regulating the C–N–P stoichiometry of soil, microbiome, and enzymes. Chemosphere, 324, 138293. https://doi.org/10.1016/j.chemosphere.2023.138293