BIOCHAR FROM AGRICULTURAL BY-PRODUCTS IN VIETNAM: A REVIEW OF AN ADSORPTION SOLUTION FOR AMMONIUM AND PHOSPHATE REMOVAL IN WASTEWATER

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ABSTRACT

Vietnam’s agricultural sector, which plays a pivotal role in ensuring national food security and bolstering the country’s global agricultural export position, faces significant environmental challenges, especially nutrient pollution due to excessive ammonium (NH_4^+) and phosphate (PO_4^{3-}) from agricultural practices. While crop residues such as rice straw, husks, and bagasse are generated in vast quantities, they remain largely underutilized, contributing to environmental degradation, including eutrophication of inland water ecosystems. This review examines the potential of agricultural by-products, particularly biochar, as eco-friendly adsorbents to mitigate nutrient pollution. Biochar, produced through the pyrolysis of agricultural residues, has shown significant promise in adsorbing NH_4^+ and PO_4^{3-} from wastewater. The study highlights various treatment methods, such as the modification of biochar with metal oxides and other chemical treatments, to enhance its adsorption capacity. This review also emphasizes the feasibility of using these low-cost, locally available materials to develop sustainable solutions for wastewater management in Vietnam, particularly in rural areas where traditional wastewater treatment technologies are often unaffordable or impractical.

Keywords: Biochar, agricultural waste, nutrient pollution, circular economy, Vietnam agriculture, ammonium (NH_4^+), and phosphate (PO_4^{3-}).

1. INTRODUCTION

Vietnam's agricultural sector is evolving, blending traditional farming methods with innovative, sustainable practices while also grappling with increased waste generation. The development of the agricultural sector generates significant economic value alongside considerable amounts of waste byproducts. By-products such as straw, rice husks, bagasse, coconut fiber, and others-which account for a large proportion of total agricultural solid waste-are often not treated or used effectively. In addition, the widespread use of chemical fertilizers and pesticides in farming has increased environmental pollution, especially eutrophication in inland water ecosystems. Compounds containing nitrogen (mainly ammonium, NH_4^+) and phosphorus (in the form of phosphate, PO_4^{3-}) remaining in soil and water can cause algal blooms, reduce dissolved oxygen, and affect public health as well as water security [1-3].

Currently, the forms of agricultural waste reuse in Vietnam are very diverse, but their efficiency and adoption depend largely on technological requirements, investment costs, and operational capabilities. The industrial and energy sectors, particularly in processes like biomass combustion, biogas production, construction material manufacturing, and recycled paper processing, necessitate advanced technologies, considerable capital investments, and well-coordinated operations [4]. Although these models add value and help reduce dependence on fossil fuels, they have not been widely replicated due to the lack of infrastructure and stable markets, especially in rural areas. Meanwhile, household-friendly solutions such as producing organic fertilizers (composting), making animal feed, and covering beds to retain moisture are considered accessible, low-cost, and make good use of available raw materials. Inconsistent technical processes hinder efficiency and compromise product quality.

Notably, the trend of applying biochar derived from agricultural by-products is opening up a promising direction: both treating solid waste and improving soil quality, while also serving as a viable adsorbent for water treatment applications. This approach aligns with the circular economy model, helping farmers become more proactive in production while contributing to the reduction of emissions and environmental pollution [5].

Nutrient pollution caused by ammonium (NH_4^+) and phosphate (PO_4^{3-}) is one of the main causes of eutrophication in agricultural areas, requiring treatment solutions that are both effective and suitable for local conditions [6]. Conventional treatment techniques like ion exchange, chemical precipitation, and biological processes (such as nitrification-denitrification and EBPR) are effective but demand advanced technology, substantial investment, rigorous operational management, and may not be suitable in all cases for small-scale or household farmers. Meanwhile, modern systems such as Anammox, MBR, or A^2O are mainly suitable for large urban areas and are difficult to deploy in rural areas of Vietnam. In that context, adsorption is considered the most feasible solution thanks to its low cost, ease of implementation, and use of readily available materials, making it especially suitable for household and cooperative scales [7].

Studies have shown that adsorbent materials derived from agricultural by-products-such as rice husks, coconut fiber, and sugarcane bagasse-after treatment can effectively adsorb both NH_4^+ and PO_4^{3-} while limiting the generation of toxic by-products. When combined with nutrient recovery processes (e.g., struvite precipitation), these materials can also be reused as fertilizers, contributing to the promotion of a circular economy in agricultural production. However, raw materials often have low adsorption efficiency due to small surface area, limited capillary structure, and lack of active functional groups [8]. Therefore, the modification of materials is a crucial area of study for boosting treatment performance. Current modification techniques include impregnation with metal oxides (Fe, Al, Mg) to increase the ability to retain PO_4^{3-} ions, thermal or alkali activation to expand the capillaries, and attachment of amine groups to increase affinity for NH_4^+. Results from many studies show that biochar modified with iron oxide or magnesium can increase the efficiency of phosphate treatment by 3–5 times, while pH adjustment or combination When used alongside zeolites, the capacity to remove ammonium is improved [8].

Considering that most agricultural production in Vietnam is still small-scale, priority must be given to leveraging by-products to develop sustainable, affordable materials for internal agricultural reuse. Focusing on simple technologies tailored to local conditions, alongside strong technical and policy support, will be essential for transforming waste into valuable resources and promoting sustainable agricultural development in the future. By leveraging inexpensive, readily modifiable raw materials with broad applications across sectors such as agricultural wastewater treatment, aquaculture, and industrial water management, adsorbents sourced from agricultural waste play a dual role in pollution reduction and the creation of a sustainable value chain that supports Vietnam's vision of circular agriculture and environmental stewardship [2, 9].

The goal of this study is to systematically review research from both global and Vietnamese contexts on employing agricultural by-products as adsorbent materials for nutrient pollution control, with a particular focus on evaluating whether Vietnam's abundant biomass resources could perform similarly or even more effectively. By highlighting both the scientific basis and practical relevance of these materials, the study aims to uncover the potential of transforming Vietnam's agricultural waste into high-value environmental solutions. This rationale forms the foundation for the research titled: "*Biochar from Agricultural By-Products: A Review of an adsorption Solution for Ammonium and Phosphate Removal in Vietnamese Wastewater"* The study contributes to the broader discourse on sustainable waste management, emphasizing the feasibility of locally driven, low-cost innovations in line with national strategies for circular economy and green agriculture.

2. VIETNAM'S AGRICULTURE: GROWTH POTENTIAL AND ENVIRONMENTAL POLLUTION CONCERNS

In 2022, crop residues in Vietnam account for 56.2% of the total agricultural by-products, amounting to approximately 159 million tons annually. These residues consist of various materials such as rice straw, rice husks, corn stalks, sugarcane bagasse, and discarded fruits and vegetables, which are produced in significant quantities and widely distributed across rural areas of Vietnam. Among these, rice straw constitutes the largest share, estimated at around 42.8 million tons [10]. Despite the large quantity of crop residues, only about 52.2% are collected and recycled. This highlights the untapped potential of these agricultural by-products and opens up significant opportunities for research into their recycling and reuse, especially in addressing nutrient pollution (ammonium and phosphate), which is a pressing environmental issue in many rural areas [11].

Table 1. Waste types and their potential applications in sustainable resource management

Waste type	Description	Potential Applications
Crop Residues	Crop residues after harvest, such as rice straw, rice husks, corn stalks, sugarcane bagasse, etc., represent a significant resource that has not been fully recycled.	Biochar production from rice straw and rice husks: Biochar derived from rice straw and rice husks has the potential to effectively adsorb pollutants such as ammonium and phosphate in wastewater [12].
		Using rice husks as organic fertilizer: Rice husks can be utilized to improve the chemical properties of soil and enhance crop yields [13].
		Using sugarcane bagasse as livestock feed: Sugarcane bagasse can be processed and used as livestock feed, improving rumen fermentation and digestion efficiency [14].
Livestock Waste	Includes manure from livestock and poultry, as well as liquid waste from animal husbandry, which represent a significant proportion of agricultural by-products and	Biogas production from livestock manure: Livestock manure can be utilized in biogas systems to generate renewable energy and reduce greenhouse gas emissions [15].
		Organic fertilizer production from poultry manure: Poultry manure can be processed into

	have high potential for recycling.	organic fertilizers, improving soil fertility and crop productivity [16].
Seafood and forestry waste	These are by-products such as shrimp shells, crab shells, and fish bones from seafood processing, which can be effectively recycled to reduce waste.	Organic fertilizer production from shrimp shells: Shrimp shells can be used to produce organic fertilizers, enhancing soil quality and increasing crop yields [17].
		Chitin and chitosan extraction from shrimp shells: Chitin and chitosan from shrimp shells can be used in the production of cosmetics, food products, and biomedical applications [18].

Table 1 presents the estimated agricultural solid waste in Vietnam by crop type, offering a more detailed breakdown of the volumes produced by different agricultural activities.

Despite the large quantity of crop residues, only about 52.2% are collected and recycled [19]. This highlights the untapped potential of these agricultural by-products and opens up significant opportunities for research into their recycling and reuse, particularly in addressing nutrient pollution (ammonium and phosphate), which is a pressing environmental issue in many rural areas. Figure 1 provides a visual representation of the agricultural waste composition, illustrating the relative proportions of crop, livestock, and seafood waste in Vietnam. This diagram gives a clearer understanding of how agricultural by-products are distributed and their potential for recycling and reuse.

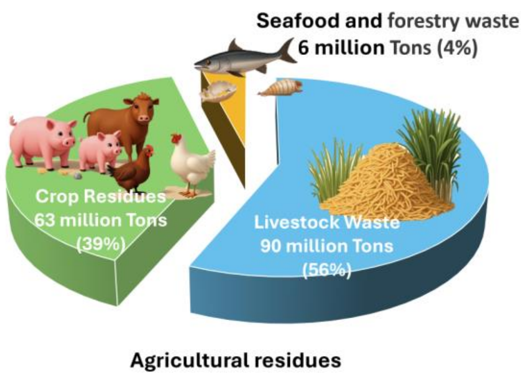

Figure 1. Agricultural waste composition

The large scale of crop residues, with an annual production of 90 million tons, underscores their high availability for various applications, particularly in pollution treatment and the development of value-added products. Given their widespread production, crop residues are a valuable resource that can contribute significantly to addressing environmental challenges. Moreover, these residues are rich in organic and nutritional components such as cellulose, lignin, hemicellulose, and minerals, making them ideal materials for creating adsorbents or biochar. These can be applied in wastewater treatment and improving soil quality [20].

However, crop residues, particularly rice straw and rice husks, are often improperly disposed of, either burned or discarded, leading to significant environmental degradation. Open-field burning remains the most common method, with approximately 45% of rice straw and coffee husks incinerated after each growing season. This practice not only leads to the loss of valuable organic material but also contributes to greenhouse gas emissions, including CO_2 and CH_4, and creates air pollution through PM2.5 particulates. Furthermore, direct dumping into irrigation canals, ponds, and fields continues to be widespread in rural areas, obstructing water flow, releasing harmful gases such as H_2S, and contaminating groundwater. In some cases, attempts to produce compost from agricultural residues fail due to inadequate control over temperature and decomposition time, resulting in the proliferation of pathogens and unpleasant odors [17, 18].

Beyond organic waste, pollution from chemical inputs such as fertilizers and pesticides has become increasingly alarming, especially in key agricultural regions like the Mekong Delta, Central Highlands, and Southeastern Vietnam. It is estimated that up to 70% of nitrogen and phosphorus fertilizers are not absorbed by crops but leach into surface and groundwater, contributing to eutrophication. Water samples from these regions often exceed national standards for nitrate (NO_3^-) and phosphate (PO_4^{3-}) concentrations as outlined in QCVN 08-MT:2015. Moreover, pesticide residues have been detected in fish ponds, groundwater wells, and farmland, posing long-term risks to human health and aquatic ecosystems. According to a joint report by the Ministry of Natural Resources and Environment and UNDP (2021), agricultural activities in Vietnam generate more than 156 million tons of solid waste annually. Rice cultivation alone contributes around 20 million tons of straw and stubble after each harvest. Industrial crops such as coffee, cashew, and pepper, along with fruit production, also generate substantial processing waste [23]. For instance, coffee husks and pulp generate approximately 1.2 million tons per year, while cashew shells account for 500,000 tons annually, which can be hazardous if not disposed of properly. Additionally, more than 1.5 million tons of fruit residues, including those from dragon fruit, durian, jackfruit, and bananas, are produced from post-harvest processing, yet these remain largely underutilized.

Vietnam's agricultural sector has experienced significant growth in recent decades, playing a vital role in ensuring national food security and strengthening the country's position in global agricultural exports. Contributing over 12% to national GDP and employing nearly 35% of the labor force, agriculture remains a cornerstone of the Vietnamese economy. However, alongside this success, there is growing pressure on the environment, primarily due to the increasing volume of solid waste generated by both cultivation and post-harvest processing activities. Inefficient waste management and weak regulatory control have led to mounting concerns over soil degradation, water pollution, and public health.

3. TECHNOLOGIES FOR PROCESSING WASTE MATERIALS AND APPLICATIONS IN POLLUTION TREATMENT

3.1. Current agricultural residue treatment technologies

In the context of sustainable agriculture and a circular bioeconomy, agricultural residue treatment technologies are increasingly being utilized to transform biological waste into high-value products, such as adsorbent materials. Current methods for treating agricultural residues include pyrolysis, aerobic fermentation, and various physical and chemical treatments.

Pyrolysis is a thermal decomposition process carried out under anaerobic conditions, typically at temperatures between 300 and 700 °C, resulting in the production of biochar. Biochar is a highly effective adsorbent due to its porous structure, large surface area, and ion retention capacity. It has shown significant potential for adsorbing pollutants such as ammonium and phosphate, making it an ideal material for wastewater treatment. Biochar derived from agricultural residues like rice husks, rice straw, and sugarcane bagasse can effectively remove ammonium and phosphate [24].

Aerobic fermentation is another method that reduces odors and stabilizes the organic components of residues. This process also transforms these residues into functional materials like humic acid, which can bind with nutrient ions, enhancing their adsorption properties. Recent research indicates that aerobic fermentation not only stabilizes residues but also enriches humic acid and other organic compounds, giving them adsorption functionality [25].

Lastly, drying, grinding, and acid/alkali treatment are physical and chemical methods aimed at increasing the surface area and enhancing the microporous structure of agricultural residues. These treatments play an essential role as a pre-treatment for adsorbents in further applications, such as wastewater treatment. Drying, grinding, and chemical treatments like acid or alkali modification improve the structure of the materials, increasing their adsorption capacity.

Together, these technologies form the backbone of current methods for converting agricultural residues into valuable adsorbent materials for pollution control, particularly in the treatment of nutrient contamination in wastewater.

3.2. Characteristics of adsorbent materials from agricultural residues

The mechanism of nutrient removal by adsorbent materials, particularly those derived from agricultural waste and by-products, involves a complex interplay of physical and chemical interactions that facilitate the capture of nutrient ions such as phosphate (PO_4^{3-}) and ammonium (NH_4^+) from aqueous solutions. The adsorption process initiates with the transfer of nutrient ions from the bulk solution to the boundary layer adjacent to the adsorbent surface, followed by diffusion through this layer to the external surface of the adsorbent. Subsequently, the ions penetrate into the pores and internal structure of the adsorbent and ultimately bind to active sites on the surface through either physical attraction or chemical bonding. Physical adsorption (physisorption) is primarily governed by van der Waals forces and electrostatic interactions, which are typically rapid and reversible. In contrast, chemical adsorption (chemisorption) entails the formation of stronger chemical bonds between nutrient ions and functional groups on the adsorbent surface; this process often requires activation energy and proceeds at a slower rate.

Agricultural waste materials inherently contain functional groups such as hydroxyl (-OH), carboxyl (-COOH), and amine (-NH_2) within their cellulose, hemicellulose, and lignin components, providing active sites that predominantly favor the adsorption of cations. However, the naturally negative surface charge of these materials limits their capacity to adsorb anions like phosphate and nitrate efficiently [26]. To overcome this limitation, various surface modification techniques have been widely employed. These include metal loading with elements such as iron (Fe), aluminum (Al), manganese (Mn), and zirconium (Zr) to introduce positively charged sites; acid treatment to enhance surface protonation and thus increase positive surface charge; and grafting of quaternary ammonium groups to create functional anion exchange sites [27]. Additionally, thermal and chemical activation methods have been utilized to improve adsorption performance by increasing the surface area and porosity of the adsorbents.

Adsorbent materials derived from agricultural residues such as coffee husks, sugarcane bagasse, and coconut coir demonstrate considerable potential for the removal of ammonium and phosphate due to their distinct physicochemical properties and adsorption mechanisms. These materials possess various functional groups (-OH, -COOH, -NH_2) that facilitate nutrient ion binding through chemical adsorption or hydrogen bonding and coordination [28]. Their porous structure and surface area are critical determinants of adsorption efficiency. For instance, biochar produced from rice straw and coconut coir exhibits a Brunauer-Emmett-Teller (BET) surface area ranging from 200 to 500 m^2/g, characterized by abundant micro- and mesopores that enhance pollutant adsorption capacity [29].

Beyond chemical composition, these materials also display significant ion exchange capabilities. Cations such as calcium (Ca^{2+}) and magnesium (Mg^{2+}) present in biochar can directly exchange with ammonium and phosphate ions in wastewater, a mechanism particularly prominent in biochars with high mineral content. The presence of surface functional groups (-OH, -COOH, $-NH_2$) further facilitates ion binding, augmenting nutrient removal efficiency [30]. The pore structure of biochar plays a pivotal role in enhancing adsorption capacity; pyrolysis-derived rice straw biochar, for example, contains an extensive network of nano- and micropores with surface areas up to 300–500 m^2/g, thereby improving physical adsorption. Enrichment of biochar with Ca^{2+} and Mg^{2+} intensifies the ion exchange process, contributing further to nutrient elimination from wastewater.

Collectively, the chemical composition, ion exchange properties, and porous architecture of agricultural residue-derived adsorbents confer high efficacy in wastewater treatment applications, particularly for the removal of harmful nutrients such as ammonium and phosphate.

3.3. Improved and modified adsorbent materials

Adsorbent materials derived from agricultural waste typically undergo various processing technologies to enhance their capacity for removing nutrients such as ammonium, phosphate, and nitrate. Common methods include pyrolysis, chemical modification, metal loading, and thermal activation. Each technique directly affects the surface structure, chemical composition, and adsorption performance of the material.

First, pyrolysis is the thermal decomposition of biomass in an oxygen-limited environment, typically carried out at temperatures between 300°C and 700°C, producing biochar—a carbon-rich solid with a porous structure. The pyrolysis temperature significantly influences the surface area, porosity, and surface functional groups of the biochar. Higher temperatures generally increase surface area and pore volume but may reduce oxygen-containing functional groups such as hydroxyl (-OH) and carboxyl (-COOH), which are essential for ion exchange and chemical adsorption. For ammonium removal, biochars produced at low to moderate pyrolysis temperatures (~300–500 °C) tend to retain more functional groups favorable for ammonium adsorption via ion exchange. In contrast, biochars produced at higher temperatures (~600–700 °C) have greater surface area, improving physical adsorption but potentially decreasing ammonium adsorption capacity due to the loss of these functional groups [31]. Regarding phosphate and nitrate removal, unmodified biochars often have limited capacity due to electrostatic repulsion between negatively charged biochar surfaces and anionic species.

Next, chemical modification is employed to alter the surface chemistry of biochars to improve nutrient adsorption. Treatments with acids (e.g., HCl, H_2SO_4) or bases (e.g., NaOH) modify surface charge and functional groups, increasing positive charge and enhancing adsorption of anions such as phosphate and nitrate by reducing electrostatic repulsion [32]. Mild oxidation treatments (e.g., with H_2O_2) introduce additional oxygen-containing groups, which can improve cation adsorption capacity, though effects on overall nutrient removal may be limited [32]. Additionally, grafting cationic polymers such as poly(diallyldimethylammonium) chloride (pDADMAC) onto biochar surfaces creates positively charged sites, substantially enhancing phosphate adsorption through anion exchange.

Metal loading and impregnation is one of the most effective methods to increase biochar adsorption capacities, especially for anionic nutrients. Metals and metal oxides such as iron (Fe), aluminum (Al), magnesium (Mg), manganese (Mn), zirconium (Zr), and lanthanum (La) can be incorporated by soaking biomass feedstocks in metal salt solutions prior to pyrolysis or by post-pyrolysis treatment of biochar in metal salt solutions [33]. These metal oxides provide positively charged adsorption sites that bind anions like phosphate via ligand exchange and precipitation mechanisms, including the formation of complexes such as struvite ($MgNH_4PO_4 \cdot 6H_2O$). Magnesium and calcium loading are particularly effective in enhancing phosphate removal through precipitation. Studies have demonstrated that metal-modified biochars have significantly higher adsorption capacities for ammonium, nitrate, and phosphate compared to unmodified biochars, with phosphate adsorption capacities reaching up to 835 mg P/g in MgO-modified biochar derived from sugar beet tailings [34].

Finally, thermal activation involves heating biochar at elevated temperatures in the presence of activating agents such as steam, CO_2, or chemicals to increase porosity and surface area. This process increases the number of physical adsorption sites and overall adsorption capacity but may reduce the abundance of surface functional groups necessary for chemical adsorption and ion exchange.

Table 2 is a list of some studies on adsorbent materials produced from agricultural by-products and some results of treating ammonium or phosphorus in water.

Table 2. Agricultural waste converted into adsorbent
to remove Phosphate and Ammonium pollution from wastewater

No.	Waste type	Adsorbent	Adsorbate	Initial Concentration (mg/L)	Adsorption Capacity (mg/g)	Reference
1	Coconut shell fiber	Addition of $LaCl_3$, quaternization, alkali modification	PO_4^{3-}	60	200.57	[35]
2	Tea leaves	Amine cross-linked	PO_4^{3-}	60-800	98.72	[36]
3	Wood waste	modified with Mg	PO_4^{3-}	360	117	[37]
4	Corn waste	modified with Mg	PO_4^{3-}	250	89	[38]
5	Wheat straw	modified with Mg-Al	PO_4^{3-}	100	153	[39]
6	Ground coffee waste	biochar modified with Mg	PO_4^{3-}	125	56	[40]
7	coconut shell biochars	modified iron oxide	PO_4^{3-}	8	9.41-22.14	[41]
8	Walnut shell biochar	modified with carboxyl	PO_4^{3-}	20	40	[42]
9	Biochar from canna	modified by $La(OH)_3$	PO_4^{3-}	50	37	[8]

10	Coconut shell-activated carbon	Chemical activation using phosphoric acid	NH_4^+	50–2000	2.26	[24]
11	Barbecue bamboo charcoal	Pyrolysis of biomass in anoxic conditions	NH_4^+	60	1.75	[43]
12	Peanut shells	Alkali treatment with NaOH	NH_4^+	10–500	313.9	[44]
13	Corncobs	Alkali treatment with NaOH	NH_4^+	10–500	373.1	
14	Cotton stalks	Alkali treatment with NaOH	NH_4^+	10–500	518.9	
15	Pyrolyzed wood biochar	Pyrolysis of biomass in anoxic conditions	NH_4^+	250–1400	44.64	[45]
16	Rice husk biochar	Pyrolysis of biomass in anoxic conditions	NH_4^+	250–1400	39.8	
17	Cacao shell biochar	Different treatments, including rinsing and leaching	NH_4^+	0.1–50	0.852	[7]
18	Oak sawdust biochar	Involvement of $LaCl_3$ (lanthanum chloride)	NH_4^+	25.7	10.1	[6]

These processing technologies synergistically optimize the characteristics of agricultural waste-derived adsorbents, enhancing their efficiency in removing harmful nutrients such as ammonium, phosphate, and nitrate from wastewater and natural water bodies. Nonetheless, challenges remain, including nutrient leaching from biochar itself, competition from other ions in water, and environmental concerns related to chemical modification processes.

4. CHALLENGES AND OPPORTUNITIES IN APPLYING BIOCHAR FOR NUTRITIONAL TREATMENT IN VIETNAM

Biochar has emerged as an effective solution for addressing nutrient pollution, specifically ammonia and phosphate, in water. As a key component in the nitrogen cycle, ammonia is an essential nutrient, but when its levels exceed safe thresholds in aquatic environments, it can degrade water quality, contributing to eutrophication and harmful algal blooms (HABs). Biochar, a carbon-rich material produced through the pyrolysis of organic matter, has been extensively studied and proven to be efficient in removing ammonia from water. A study in China demonstrated that modified biochar can absorb ammonia with a remarkable capacity of up to 518.9 mg/g, highlighting its effectiveness in treating wastewater contaminated with ammonia, particularly from agricultural or industrial sources. Ammonia absorption efficiency is influenced by factors such as pH and temperature. Research indicates that biochar modified in a neutral pH environment (around 6-8) optimizes its ammonia absorption capacity, making it highly efficient for water treatment applications [32, 33].

In the context of Vietnam, biochar can be employed to treat ammonia pollution originating from agricultural practices, particularly the use of chemical fertilizers and livestock manure. According to the National Environmental Report, agricultural and livestock waste accounts for around 30% of water pollution in rural areas of Vietnam. This makes biochar an invaluable tool for addressing ammonia contamination and improving water quality in affected regions.

Phosphate (PO_4^{3-}) is another critical nutrient that can cause environmental issues when present in excess. Although phosphate is essential for plant growth, excessive concentrations can lead to eutrophication and disrupt aquatic ecosystems. Biochar has demonstrated significant potential in removing phosphate from water, especially when modified with metals like Fe or Al [7, 25]. Studies show that modified biochar can absorb phosphate at capacities of 50 mg/g or higher, offering an effective means to reduce phosphate pollution in water bodies. Biochar contains surface functional groups that bind with phosphate ions, preventing their spread into water sources and reducing the risk of eutrophication. This characteristic makes biochar particularly useful in treating phosphate pollution resulting from agricultural runoff and industrial wastewater.

Biochar can be utilized in wastewater treatment systems to filter and reduce phosphate concentrations, particularly in areas related to fertilizer production or livestock farming [48]. Applying biochar can contribute to preserving and protecting natural water resources, promoting healthier aquatic ecosystems. The dual functionality of biochar in treating both ammonia and phosphate makes it a valuable tool in tackling nutrient pollution, a significant environmental concern in developing and developed regions alike, including Vietnam.

The environmental benefits of biochar extend beyond nutrient pollution treatment. By using biochar to treat agricultural waste, it can also play a role in mitigating climate change. Research from the International Biochar Initiative shows that biochar has the potential to sequester up to 2 billion tons of CO_2 per year globally [49]. This means biochar not only addresses water and soil pollution but also helps reduce greenhouse gas emissions, offering a dual benefit of improving environmental health and combating climate change.

In addition to its environmental benefits, biochar presents significant economic potential. Research from the Vietnam Agricultural Research Institute suggests that using biochar as an organic fertilizer could generate approximately 4 million VND per ton from agricultural by-products like rice straw [11]. This demonstrates that biochar is not only an environmentally sustainable solution but also an economically viable product. It creates new revenue streams by converting agricultural waste into a valuable resource, contributing to the development of a circular economy. Consequently, biochar presents a promising opportunity for Vietnam to address environmental challenges while fostering economic growth.

Despite its potential, several challenges hinder the widespread adoption and application of biochar, particularly in Vietnam. One of the primary challenges is the high initial investment and production costs. Producing biochar from agricultural waste requires specialized equipment and infrastructure, and setting up biochar production facilities can involve significant initial costs, ranging from 500 million to 2 billion VND for smaller-scale operations [11]. This presents a substantial barrier, especially for small farmers and businesses that may not have access to sufficient capital or financing options. Additionally, the expenses associated with modifying biochar, such as using alkali treatments to enhance its adsorption properties, further add to the overall production costs, making it an expensive technology to implement.

Another obstacle is the limited awareness and knowledge among key stakeholders, particularly smallholder farmers and rural communities. In Vietnam, there is a lack of widespread understanding about the environmental benefits and economic potential of biochar. Without proper education and training, farmers and businesses may not recognize the full range of applications biochar offers, such as treating nutrient pollution or enhancing soil quality. Moreover, the lack of knowledge on how to integrate biochar effectively into existing agricultural practices limits its adoption in rural areas and small-scale farming communities [50].

Additionally, the lack of policy support and regulatory frameworks is a significant barrier. Despite its potential for addressing environmental challenges, there are no comprehensive government policies or regulatory frameworks that support biochar technology in Vietnam. Farmers and businesses often lack incentives or subsidies to adopt biochar production, and the absence of clear regulations makes it difficult for producers to scale up production. The Vietnamese government has yet to establish cohesive strategies or long-term policies to promote biochar as a sustainable solution for nutrient pollution and agricultural waste management [51].

The variability in biochar quality and effectiveness also presents challenges. The performance of biochar in removing pollutants such as ammonia and phosphate depends on several factors, including the type of feedstock used, the production method, and any modifications made to improve its properties. As a result, the quality and effectiveness of biochar can vary significantly, making it difficult to standardize its use for wastewater treatment or agricultural applications. This variability requires farmers and businesses to carefully select the right type of biochar for their specific needs, complicating the widespread adoption of biochar technology [52].

Moreover, the environmental and social impacts of large-scale biochar production must be considered. While biochar offers clear environmental benefits, the large-scale collection of agricultural waste for biochar production could place additional pressure on local resources, potentially leading to the overharvesting of crop residues that would otherwise be used to maintain soil fertility. There are also concerns about the sustainability of biochar production if it results in increased deforestation or land degradation to meet the demand for feedstock. These social and environmental concerns must be addressed to ensure that biochar production remains sustainable [53].

Furthermore, insufficient research and data on the long-term effects of biochar remain an issue. While biochar has been the subject of numerous studies, more research is needed to understand its long-term impacts on soil health, water quality, and its ability to sequester carbon permanently. Without comprehensive scientific data on the full lifecycle impacts of biochar use, stakeholders may be hesitant to adopt it on a large scale due to potential risks or unknown effects on ecosystems [54].

Finally, the lack of market infrastructure for biochar is another significant challenge. For biochar to become a commercially viable product in Vietnam, a well-established market infrastructure is needed to support its production, distribution, and use. Currently, biochar is not widely marketed or sold at the national level, and access to high-quality biochar products is limited. This lack of market development contributes to the slow adoption of biochar in agriculture and environmental sectors, further hindering its potential as a mainstream solution.

5. CONCLUSION

The application of biochar derived from agricultural waste presents a promising and sustainable solution for addressing nutrient pollution in Vietnam's agricultural systems. The utilization of crop residues for biochar production not only helps reduce the environmental burden of agricultural waste but also provides an effective method for the removal of ammonium and phosphate from wastewater. While biochar production offers a dual benefit of waste management and water quality improvement, several challenges remain, including high initial investment costs, limited awareness among local farmers, and a lack of government policies and regulatory frameworks to support biochar initiatives. Nevertheless, the potential for biochar to foster a circular economy in Vietnam's agricultural sector is significant, with its ability to enhance soil quality, improve agricultural productivity, and contribute to pollution reduction. For the widespread adoption of biochar technology, increased research, policy support, and community engagement will be crucial to overcoming existing barriers and promoting the integration of biochar into Vietnam's sustainable agricultural practices.

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TÓM TẮT

THAN SINH HỌC TỪ PHỤ PHẨM NÔNG NGHIỆP TẠI VIỆT NAM: MỘT NGHIÊN CỨU TỔNG QUAN GIẢI PHÁP HẤP PHỤ LOẠI BỎ AMONI VÀ PHỐT PHÁT TRONG NƯỚC THẢI

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Ngành nông nghiệp Việt Nam đóng vai trò then chốt trong đảm bảo an ninh lương thực và thúc đẩy xuất khẩu nông sản toàn cầu, đang đối mặt với thách thức môi trường nghiêm trọng, đặc biệt là ô nhiễm chất dinh dưỡng từ amoni (NH_4^+) và phốt phát (PO_4^{3-}) dư thừa do hoạt động nông nghiệp. Các phụ phẩm như rơm rạ, vỏ trấu, bã mía, dù được tạo ra với số lượng lớn, vẫn chưa được khai thác hiệu quả, góp phần gây suy thoái môi trường, bao gồm hiện tượng phú dưỡng ở các hệ sinh thái nước nội địa. Bài tổng quan này đánh giá tiềm năng của phụ phẩm nông nghiệp, đặc biệt là biochar, như một chất hấp phụ thân thiện môi trường để giảm thiểu ô nhiễm chất dinh dưỡng. Biochar, được sản xuất từ quá trình nhiệt phân phụ phẩm nông nghiệp, cho thấy khả năng vượt trội trong việc hấp phụ NH_4^+ và PO_4^{3-} từ nước thải. Nghiên cứu làm nổi bật các phương pháp xử lý như biến tính biochar bằng oxit kim loại hoặc hóa chất để nâng cao hiệu suất hấp phụ. Bài viết cũng nhấn mạnh tính khả thi của việc sử dụng các vật liệu giá rẻ, sẵn có tại địa phương để phát triển các giải pháp quản lý nước thải bền vững tại Việt Nam, đặc biệt ở vùng nông thôn, nơi các công nghệ xử lý nước thải truyền thống thường quá tốn kém hoặc không phù hợp.

Từ khóa: Than sinh học, Chất thải nông nghiệp, Ô nhiễm dinh dưỡng, Kinh tế tuần hoàn, Nông nghiệp Việt Nam, amoni (NH_4^+), và phốt phát (PO_4^{3-}).