Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(11), 205–216
https://doi.org/10.12911/22998993/207926
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.06.10
Accepted: 2025.08.01
Published: 2025.08.15

Transforming bamboo waste into a chitosan-modified sustainable biochar adsorbent for wastewater phosphorus management

Watcharapol Wonglertarak[1], Boonchai Wichitsathian[2*], Jareeya Yimrattanabovorn[2], Pornvarin Makhliem[1], Maturada Khowattana[2], Wimonmas Boonyungyuen[1]

[1] Environmental Engineering and Disaster Management Program, School of Interdisciplinary Studies, Mahidol University, Kanchanaburi Campus, Kanchanaburi, Thailand

[2] Institute of Engineering, School of Environmental Engineering, Suranaree University of Technology, Nakhon Ratchasima, Thailand

* Corresponding author's e-mail: boonchai@sut.ac.th

ABSTRACT

The escalating concentration of phosphorus in wastewater, primarily from industrial and agricultural activities, poses a critical environmental threat. This surplus phosphorus is a major driver of eutrophication, leading to severe adverse impacts on aquatic ecosystems, including oxygen depletion, biodiversity loss, and overall water quality degradation, ultimately affecting human health. Consequently, developing effective and sustainable strategies for phosphorus removal from wastewater before its environmental discharge is an imperative research priority. This study aimed to engineer an efficient and environmentally benign phosphorus adsorbent by valorizing locally abundant agricultural waste: bamboo waste. The bamboo waste was converted into biochar via controlled pyrolysis at 500, 600, and 700 °C for 2 hours. Subsequently, the biochar's surface was chemically modified with chitosan, a natural biopolymer, to enhance its phosphate adsorption efficiency. Adsorption performance was rigorously evaluated using synthetic wastewater with a phosphate concentration of 20 mg PO_4^{3-}/L. Findings revealed that the chitosan-modified bamboo biochar pyrolyzed at an optimal 600 °C exhibited the most promising characteristics. This adsorbent demonstrated a significant 30.59% increase in iodine adsorption capacity compared to unmodified biochar, indicating enhanced surface area and porosity. Crucially, it achieved the highest phosphate adsorption capacity of 0.76 mg/g, representing a substantial 17.71% increase over samples produced at other temperatures. This study confirms the remarkable potential of chitosan-modified bamboo biochar as a sustainable adsorbent material for advanced phosphorus management in wastewater treatment. This innovative approach not only contributes to efficient wastewater purification but also offers a valuable pathway for upcycling agricultural waste, aligning with principles of sustainable materials and circular economy, with potential for future applications in adsorbing other pollutants.

Keywords: biochar, chitosan modification, bamboo waste, adsorption, phosphorus removal, wastewater treatment, eutrophication, sustainable materials.

INTRODUCTION

Water pollution is a significant and pressing environmental challenge in Thailand today. Its primary causes stem from escalating human activities, including increased domestic wastewater discharge, industrial effluent release, and chemical runoff from agricultural practices. These wastewater streams are sources of various pollutants, notably phosphorus. Phosphorus, an essential nutrient in chemical fertilizers widely used in agriculture, is often leached into natural water bodies over time, leading to its excessive accumulation. While phosphorus is vital for the sustenance of living organisms, its presence in quantities exceeding standard thresholds can severely lead to eutrophication. This phenomenon is characterized by the rapid and abnormal proliferation of green algae. When these algal blooms eventually die and decompose by microorganisms, particularly during nighttime, they critically deplete the dissolved oxygen levels in water [Kyriakopoulos et al., 2022]. This depletion results in a drastic decline in water quality, loss of aquatic biodiversity, and severe damage to the entire aquatic ecosystem. Eutrophication is a pervasive and intensifying problem across many regions of the country, with ongoing concerns regarding agricultural runoff impacts [Xia et al., 2020]. The phosphorus content in water bodies exhibits significant variability, influenced by both point and non-point sources in their vicinity. Various sources contribute to phosphorus pollution, with concentrations ranging widely. For instance, high amounts are observed in sewage water (470–1070 mg/L), dairy wastewater (350–450 mg/L), and discharges from the anodizing industry (620–5069 mg/L). Specifically, domestic wastewater typically contains phosphorus concentrations ranging from 5–20 mg/L, and wastewater from the fertilizer industry averages around 24 mg/L [Parasana et al. 2022].

Consequently, developing efficient and sustainable methods for phosphorus removal from wastewater before its discharge into the environment is a matter of paramount national and global importance. Various phosphorus removal techniques have been developed, including chemical precipitation, ion exchange, membrane filtration, and adsorption [Witek-Krowiak et al., 2022]. Recent advances in phosphorus removal technologies continue to emphasize sustainability and resource recovery [Zhang et al., 2025]. Among these, adsorption stands out as a particularly attractive and highly suitable technique for phosphorus removal from wastewater. This is due to its low operating cost, ease of implementation, flexibility in controlling operational conditions, and relatively simple procedures [Usman et al., 2022; Priya et al., 2022]. Its appeal is further enhanced when adsorbents are developed from readily available local agricultural waste materials. For instance, bamboo waste, a significant byproduct from product processing in communities. Despite some existing utilization in other applications, a substantial amount of bamboo waste remains unutilized. Thus, developing these bamboo residues into phosphorus adsorbents not only contributes to addressing water pollution but also adds value and promotes the sustainable utilization of agricultural waste, aligning with the principles of the circular economy and sustainable development [Kalderis et al., 2023].

Previous research has extensively explored biochar, a highly porous carbonaceous material derived from biomass, as a promising adsorbent. The utilization of agricultural waste for biochar production has gained widespread attention, with examples including apricot kernels, corn cobs, corn husks, coconut shells, hardwoods, date palm trunks, bamboo, rice husks, and marigold stalks [He et al., 2022; Huang et al.,2019]. Biochar has been applied in various environmental remediation efforts, including water pollution treatment, through its mechanism of adsorbing pollutants or heavy metals within its porous structure [Liang et al., 2021]. Numerous studies support the diverse properties of biochar, such as reducing fermentation time and nitrogen release, improving soil quality, adsorbing gases and reducing odors, nitrogen fixation, and adsorbing mineral contaminants like phosphates and nitrates, as well as various chemicals and heavy metals. However, naturally occurring biochar typically possesses a negatively charged surface, which inherently limits its capacity to adsorb highly negatively charged substances, such as orthophosphate and organophosphate (the predominant forms of phosphorus in water), due to electrostatic repulsion [Joshi et al., 2023]. This inherent limitation necessitates further modification for enhanced anionic pollutant removal [Geca et al., 2023]. Therefore, enhancing the phosphorus adsorption capacity of biochar through surface modification becomes imperative.

Currently, surface modification of biochar has become a crucial strategy to engineer new structures and surface properties, thereby improving its contaminant removal efficiency. Novel biochar materials with enhanced chemical and physical properties are actively being developed for this purpose. Biochar modification methods to boost contaminant adsorption can broadly be categorized into four main groups: chemical modification, physical modification, mineral impregnation, and magnetic modification [Bao et al., 2022]. Generally, these modifications aim to increase specific surface area, enhance the quantity of oxygen-containing acidic functional groups, develop porosity, and alter surface elemental composition, all of which are critical factors for contaminant adsorption. For example, acid treatment can induce positive charges on the biochar surface, and the protonation of surface hydroxyl groups significantly increased the adsorption capacity for Cu, Zn, and Cd by dairy manure-derived biochar [Rangabhashiyam and Balasubramanian al., 2019]. Recent studies also show the effectiveness of various chemical modifications for heavy metal removal [Liu et al., 2022]. Furthermore, the surface area and porous structure of biochar significantly influence heavy metal adsorption efficacy [Chin et al., 2022]. Steam-activated biochar produced from agro-residues, forestry residues, sewage sludge, fruit peels, poultry manure, and algal biomass has been reported to efficiently remove Cu^{2+} through ion exchange mechanisms [Trivedi et al., 2025].

In the context of this research, the modification of bamboo biochar with chitosan was adopted as a strategy to address environmental issues and to maximize the utility of agricultural waste. Chitosan, a natural polymer extracted from shrimp shells, is notable for its positively charged amine functional groups. These groups act as electron donors, enabling effective adsorption of negatively charged substances, including phosphorus, which predominantly exists in anionic forms. Comparative studies have shown that chitosan exhibits a remarkably high capacity for phosphorus removal compared to other modifying agents such as lanthanum, manganese, calcium, and iron. Research confirms that chitosan-modified, magnesium-impregnated corn straw biochar (CS-MgCBC) demonstrated high efficiency in removing both NH^{4+}-N and PO_4^{3-}-P from livestock wastewater. Chitosan modification significantly enhanced the biochar's surface area and functional groups, leading to superior adsorption capacities (up to 35.59 mg/g for NH^{4+}-N and 221.89 mg/g for PO_4^{3-}-P). This modification improved the biochar's performance by 48.3% for NH^{4+}-N and 68.9% for PO_4^{3-}-P, primarily via electrostatic adsorption, precipitation, and ligand exchange [Li et al., 2022]. Similarly, a study by [Manyatshe et al., 2022] demonstrated that Chitosan modified sugarcane bagasse biochar could adsorb up to 40.23% of Phosphate, further reinforcing the potential of chitosan as an effective modifying agent for biochar in removing anionic pollutants. More recent work also highlights the versatility of chitosan-biochar composites for diverse pollutant remediation, including dyes and pharmaceuticals, underscoring its broad applicability beyond heavy metals and phosphorus [Gao et al., 2022; Chin et al., 2022; Palansooriya et al., 2021].

Therefore, the primary objective of this study is to utilize abundant bamboo waste to produce an efficient and sustainable phosphorus adsorbent material. This will be achieved through a pyrolysis process to produce biochar from bamboo waste at varying temperatures (500, 600, and 700 °C). Subsequently, the physical and chemical properties of the obtained biochar will be thoroughly characterized, and its phosphorus adsorption capacity in synthetic wastewater will be evaluated. Furthermore, the potential application of this modified biochar for real wastewater treatment will be considered. The utilization of bamboo waste and chitosan, both biodegradable biomass materials, represents a promising approach for waste management and the production of environmentally friendly materials. This aligns with the principles of efficient resource utilization and waste reduction as outlined in the sustainable development goals (SDGs). The findings of this study are expected to pave the way for further development of modified biochar from waste materials for broad applications in adsorbing various other pollutants in the future [Masud et al., 2023].

MATERIALS AND METHODS

Biochar preparation

Bamboo biomass was initially pre-treated by drying in a hot air oven at 105 °C for 24 hours to remove moisture. The dried bamboo biomass was then subjected to pyrolysis in a muffle furnace at three different temperatures: 500 °C, 600 °C, and 700 °C, with the temperature held at each target level for 2 hours. After the pyrolysis process, the resulting biochar from each temperature was thoroughly rinsed with deionized (DI) water to remove any residual impurities. The washed biochar samples were then dried in an oven at 105 °C for 24 hours. Finally, the dried biochar was sieved using standard sieves: No. 35 (0.5 mm) and No. 18 (1 mm). The selected biochar particles for further use had a size range between 0.5–1 mm.

Chitosan modification of biochar

The preparation of chitosan-modified biochar (BBM) commenced with the preparation of the chitosan solution. 3 grams of powdered chitosan were dissolved in 180 mL of 2% (v/v) acetic acid solution, then continuously stirred for 30 minutes at room temperature to ensure complete dissolution of the chitosan. Subsequently, the prepared biochar was immersed in this chitosan solution at a chitosan solution-to-biochar ratio of 1:4 (v/w) [Zhou et al., 2013]. This suspension was left to soak for 30 minutes to ensure thorough chitosan impregnation into the biochar. Following this impregnation step, the chitosan-impregnated biochar was transferred and immersed in 900 mL of 1.2% (w/v) sodium hydroxide (NaOH) solution for 12 hours to promote the cross-linking process and insolubilize the chitosan on the biochar surface. The chitosan-coated biochar was then filtered and thoroughly rinsed with deionized water (DI water) until the pH of the rinse water stabilized in the range of 6.5–7.5, ensuring complete removal of residual substances. Finally, the modified biochar was dried in an oven at 105 °C for 24 hours to ensure complete moisture removal.

Phosphate adsorption experiment

To evaluate the adsorption capacity (q_e) of the prepared biochar, experiments were conducted using both unmodified biochar (BB) and chitosan-modified biochar (BBM) synthesized at pyrolysis temperatures of 500, 600, and 700 °C. For each experiment, 0.5 grams of biochar was placed into a 250 mL Erlenmeyer flask containing 50 mL of synthetic phosphate solution with an initial concentration of 20 mg PO_4^{3-}/L was strategically selected for this study. This concentration is highly relevant as it falls within the upper range commonly found in domestic wastewater. The pH of the synthetic phosphate solution during the adsorption experiments was 7.0 ± 0.2. The flasks were then agitated using an orbital shaker at a constant speed of 150 revolutions per minute (rpm) for 24 hours. Subsequently, the solution was filtered to separate the adsorbent, and the residual phosphate concentration in the supernatant was determined. The remaining orthophosphate concentration was analyzed using the Stannous Chloride Method, measuring the absorbance at a wavelength of 690 nanometers (nm) with a Spectrophotometer. The equilibrium adsorption capacity, q_e (mg/g), was calculated using the following Equation 1.

$$q_e = \frac{(C_0 - C_e)V}{m} \quad (1)$$

where: C_0 (mg/L) is the initial phosphate concentration, C_e (mg/L) is the equilibrium (final) phosphate concentration, V (L) is the volume of the phosphate solution, m (g) is the mass of the adsorbent.

Material characterization

The morphological characteristics and elemental composition of both unmodified and chitosan-modified biochar samples, including those before and after phosphate adsorption, were comprehensively analyzed. This analysis was primarily conducted using scanning electron microscopy (SEM) coupled with Energy-Dispersive X-ray Spectroscopy (EDS/EDX) to examine changes in the surface structure and the distribution of elemental components on the samples. Prior to analysis, all biochar samples were thoroughly dried. The analyses were performed using an SEM instrument (JEOL, Model JSM-IT200), coupled with energy-dispersive X-ray spectrometry (EDS) (JEOL MP-04110BED).

Statistical analysis

To thoroughly understand the complex relationships between biochar properties, pyrolysis synthesis temperatures, and their influence on phosphate adsorption performance, comprehensive statistical analyses were performed. Specifically, principal component analysis (PCA) was employed to reduce the dimensionality of the dataset and visualize the main trends and relationships among various parameters and samples. This technique helped in identifying the most influential variables and the distinct clustering of biochar types. Concurrently, Hierarchical Clustering Analysis, presented as a Dendrogram, was utilized to group samples based on their similarities in physicochemical properties and adsorption efficiencies. This allowed for the identification of natural clusters among the biochar samples prepared under different conditions. All statistical computations and visualizations were carried out using SPSS Statistics software.

RESULTS AND DISCUSSION

Characterization of bamboo biochar

Synthesis of bamboo biochar (BB) was performed via pyrolysis at 500, 600, and 700 °C for 2 hours. The resulting biochar was ground and sieved to an particle size of 0.5–1 mm. The study found that pyrolysis temperature significantly affected the biochar yield. As the temperature increased, the biochar yield continuously decreased. Biochar synthesized at 500 °C (BB500) yielded the highest amount at 28.66%, followed by 600 °C (BB600) at 16.45%, and 700 °C (BB700) yielded the lowest at 13.39%. This finding is consistent with the principle that increasing temperature during the pyrolysis process leads to more complete decomposition of organic matter in the biomass, resulting in higher liberation of volatiles and gases such as carbon dioxide (CO_2) and carbon monoxide (CO), which in turn causes greater mass loss of the raw material, thus reducing the amount of biochar obtained [Tomczyk et al., 2020]. Subsequently, the iodine adsorption capacity (Iodine Number) of bamboo biochar was analyzed both before and after modification with chitosan solution, according to ASTM D1510 standard. The experimental results are shown in Figure 1. The study found that modification of biochar with chitosan solution increased the iodine adsorption capacity of bamboo biochar at all synthesis temperatures when compared to unmodified biochar. Specifically, biochar synthesized at 600 °C (BB600) and modified with chitosan (BBM600) showed the highest increase in iodine adsorption capacity at 30.59%. This was followed by 500 °C, which showed an increase of 20.85%, and finally 700 °C, which showed the lowest increase at 7.90%. This study clearly demonstrates that chitosan modification enhanced the iodine adsorption efficiency of biochar [Gao et al., 2022].

The morphological characteristics of BB, both before and after modification with chitosan solution, were analyzed using a SEM at a magnification of 3000x. The structural morphology of the unmodified biochar samples (BB-500, BB-600, and BB-700), as shown in Figure 2, revealed a rough, uneven surface with numerous visible pores along the cross-sectional area of the structure. This indicates the decomposition of volatile organic compounds during the pyrolysis process [Díaz et al., 2024]. Due to bamboo's less dense and less rigid structure, it readily forms pores under pyrolysis conditions [Lou et al., 2023]. Further analysis of porosity properties showed that bamboo biochar possessed a high surface area, and its average pore sizes were categorized as macropores according to IUPAC standards. Specifically, biochar pyrolyzed at 500 °C (BB-500) had an average pore size of 1.8 μm, BB-600 had 1.08 μm, and BB-700 had 1.48 μm. Following the modification of these three biochar samples with chitosan solution and subsequent re-analysis of their morphology at 3000x magnification (Figure 2), it was observed that the chitosan-modified biochar exhibited reduced pore sizes across all temperatures. Specifically, the modified biochar at 500 °C (BBM-500) had a pore size of 0.63 μm, BBM-600 had 0.57 μm, and BBM-700 had 1.45 μm. This reduction in pore size is attributed to the coating of chitosan solution on the biochar's surface and within its pores, which led to a decrease in pore dimensions and consequently an increase in the material's overall surface area [Díaz et al., 2024].

Adsorption capacity and efficiency of bamboo biochar

This study systematically evaluated the phosphate adsorption capacity of BB prepared at various synthesis temperatures. Biochar samples were specifically produced at 500, 600, and 700

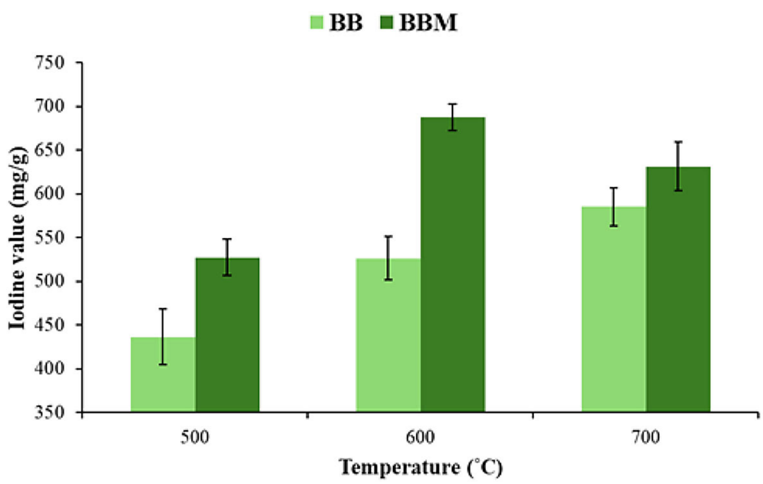


Figure 1. Iodine adsorption capacity of bamboo biochar (BB) and chitosan-modified bamboo biochar (BBM) at different pyrolysis temperatures

°C to assess the impact of pyrolysis temperature on adsorption performance. The analysis of the experimental results provided clear insights into the adsorption efficiencies. It was observed that the biochar synthesized at 600 °C exhibited the highest phosphate adsorption efficiency among the tested samples, capable of adsorbing phosphate up to 15.62%. Biochar prepared at a slightly lower temperature, 500 °C, also demonstrated considerable adsorption, achieving an efficiency of 15.32%. In contrast, the biochar synthesized at the highest temperature of 700 °C showed a noticeable reduction in performance, with an adsorption efficiency of only 12.92% (Figure 3). These findings from the experimental results suggest a distinct trend in phosphate adsorption related to pyrolysis temperature. Specifically, increasing the pyrolysis temperature from 500 °C to 600 °C consistently led to an enhancement in the values of phosphate adsorption. This improvement is primarily attributed to favorable structural changes occurring within the biochar during the pyrolysis process. Such changes often include an increase in the material's surface area and a development of its porosity, likely resulting from the more complete decomposition of organic matter and the subsequent formation of numerous small pores, which are crucial for effective adsorption [Alves et al., 2025]. However, this positive trend in adsorption capacity did not continue beyond 600 °C. A significant decrease in phosphate adsorption was observed when the synthesis temperature reached 700 °C. This decline is potentially explained by the altered characteristics of biochar produced at such high temperatures. It is understood that at temperatures exceedingly approximately 650 °C, biochar tends to become more thermally stable and increasingly hydrophobic. These changes can adversely affect its ability to adsorb phosphate by potentially leading to the loss of essential polar functional groups on the biochar surface that are vital for interaction with phosphate ions, and may also result in the collapse or fusion of pore structures, thereby reducing the overall accessible adsorption sites [Zhang et al., 2022].

The phosphate adsorption capacity of chitosan-modified BBM was systematically analyzed across different synthesis temperatures (500, 600, and 700 °C). The results consistently demonstrated higher adsorption efficiency and capacity for BBM when compared to unmodified BB. Specifically, BBM synthesized at 600 °C (BBM600) exhibited the highest performance, achieving an adsorption efficiency of approximately 17.7% and a maximum adsorption capacity of approximately 0.76 mg/g. Biochar synthesized at 700 °C (BBM700) followed closely, with an efficiency of approximately 17.12% and a capacity of approximately 0.77 mg/g. The lowest efficiency among the modified samples was recorded at 500 °C (BBM500), which yielded an efficiency

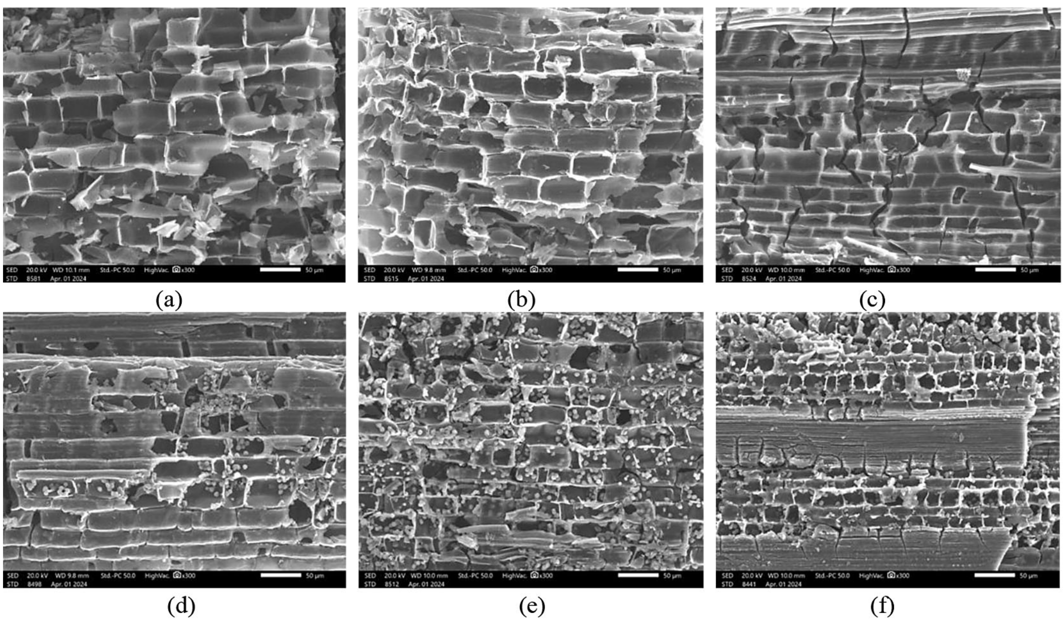


Figure 2. SEM structural morphology of bamboo biochar (BB) and chitosan-modified bamboo biochar (BBM) at different pyrolysis temperatures. (a) BB500 (b) BB600 (c) BB700 (d) BBM500 (e) BBM600 (f) BBM700

of approximately 16.22% and a capacity of approximately 0.72 mg/g (Figure 3). This overall trend indicates that chitosan modification not only generally increases the phosphate adsorption efficiency but also confirms that the optimal pyrolysis temperature of 600 °C, as observed for unmodified biochar, continues to yield the best results for the modified material.

The enhanced phosphate adsorption observed after chitosan modification is evident and marks a clear difference from experiments performed without chitosan. Unmodified bamboo biochar, which contains calcium, typically exhibits basic properties and possesses a negatively charged surface. Upon chitosan modification, the elemental composition of the biochar can change, partly due to the use of acetic acid in the modification process, which may facilitate the leaching of certain ions from the bamboo biochar. Crucially, chitosan is rich in amine groups, which function as electron donors, thereby enabling the modified biochar to achieve significantly higher efficiency in phosphate adsorption compared to its unmodified counterpart [Wujcicki et al., 2023]. This finding regarding enhanced adsorption is consistent with principles observed in previous research concerning surface charge interactions [Perera et al., 2023; Kadirvelu et al., 2001]. Conversely, investigations into the co-adsorption of lead and arsenic from solutions using chitosan-coated rock powder revealed contrasting results: lead adsorption increased, while arsenic adsorption decreased, when compared to unmodified rock powder. This differential behavior was specifically linked to the negative net surface charge of the adsorbent in that context [Kadirvelu et al., 2001].

Analysis of biochar adsorption properties and the influence of temperature

Scanning electron microscopy (SEM) images, as shown in Figure 4, reveal the surface morphology of bamboo biochar synthesized at 600 °C under different preparation conditions. Figure 4a displays the surface of unmodified biochar (BB600) before adsorption, which exhibits a clear and relatively ordered cellular pore structure, reflecting the original structure of the biomass material. Well-defined, open cellular lumens and relatively smooth cell walls are clearly observable, indicating a pristine surface devoid of foreign substances or coatings. In contrast, Figure 4b, showing unmodified biochar (BB600) after phosphate adsorption, maintains a generally similar porous structure and overall surface appearance to Figure 4a. However, subtle changes may be present on the surface, such as slight unevenness or the accumulation of small, visually imperceptible particles, which could indicate initial interaction or the attachment of phosphate ions to the surface. Nevertheless, Figure 4c, representing chitosan-modified biochar (BBM600) before adsorption, demonstrates a clear alteration of the surface compared to the unmodified biochar. A distinct film or coating of chitosan is evident, spread across the cell walls and within the pores, resulting in an overall rougher surface with a layered or granular appearance. This observation clearly confirms the successful chitosan modification process. This coating also modifies the original surface topography, potentially contributing to an increased surface area or providing additional reaction sites. Finally, Figure 4d, depicting chitosan-modified biochar (BBM600) after phosphate adsorption,

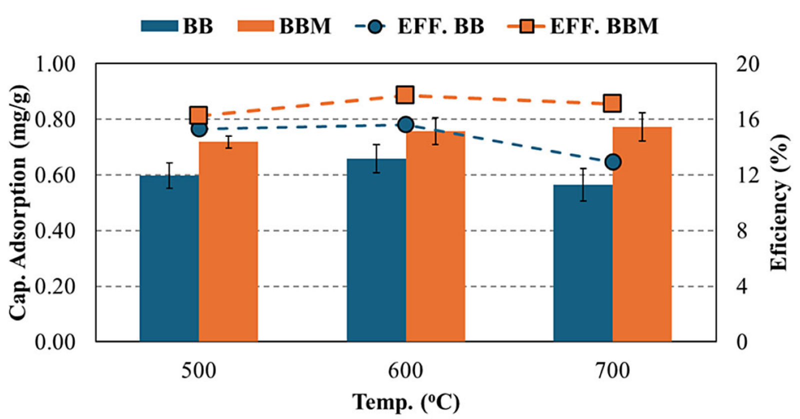


Figure 3. Phosphate adsorption capacity and efficiency of BB and BBM bamboo biochar at different pyrolysis temperatures

still shows the chitosan coating. However, further changes are observable on the surface, such as some pore lumens appearing narrower or obscured by adsorbed material, and the surface texture potentially appearing thicker or exhibiting accumulation of substances. These visual cues strongly indicate the effective immobilization of phosphate onto the chitosan layer and the surface of the modified biochar. These evident changes from the SEM images provide crucial qualitative information that supports the chemical elemental analysis results and the improved phosphate adsorption efficiency reported previously.

The elemental composition analysis of biochar samples was conducted using Energy-Dispersive X-ray Spectroscopy (EDS/EDX) to evaluate changes in elemental composition following chitosan modification and phosphate adsorption. Figure 5 presents the EDS spectra and corresponding elemental quantification for unmodified biochar (BB) and chitosan-modified biochar (BBM) after phosphate adsorption. From the analysis, both BB and BBM samples were found to primarily consist of carbon (C) and oxygen (O), which are key components of the biochar structure. Their proportions were very similar (BB: C 74.01 ± 0.34 Mass%, O 23.23 ± 0.58 Mass%; BBM: C 73.86 ± 0.31 Mass%, O 23.35 ± 0.53 Mass%), indicating that the modification process did not significantly alter these primary elements. However, a distinct change was observed in the sodium (Na) content. BB contained 2.76 ± 0.12 Mass% Na, while BBM showed a reduction to 1.45 ± 0.08 Mass% Na. This decrease in sodium is consistent with the concept of leaching of certain ions from the biochar during the modification process involving acetic acid. Most importantly, the presence of phosphorus (P) was detected. In BB, phosphorus was found in a very small amount, only 0.02 ± 0.03 Mass%. Conversely, in BBM after phosphate adsorption, the phosphorus content significantly increased to 0.14 ± 0.03 Mass%. The increased presence of phosphorus in the modified biochar serves as direct empirical evidence of successful phosphate adsorption and confirms the material's efficiency in capturing phosphorus, which is consistent with previous experimental adsorption efficiency results.

This study analyzed the adsorption properties of biochar produced at different temperatures using PCA to understand the structural relationships for adsorption between the studied variables (Bamboo Biochar, BB; and modified bamboo biochar, MBB) and the experimental outcomes at various pyrolysis temperatures (500 °C, 600 °C, and 700 °C). The results are presented in a factor loading plot (Figure 6). The two principal components (F1 and F2) collectively explained 100% of the total data variance, indicating that these two components are sufficient to effectively describe all variations within the dataset. Specifically, the F1 axis contributed significantly, accounting for 75.00% of the variance, thus representing the

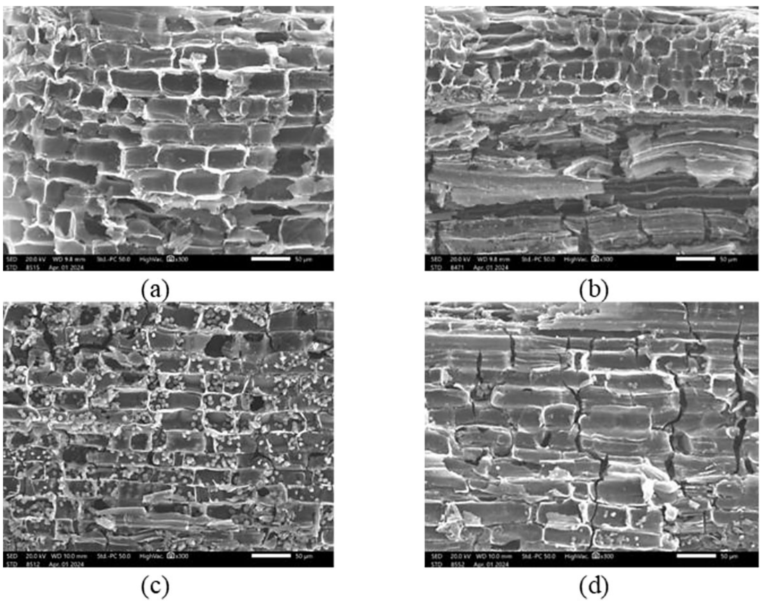
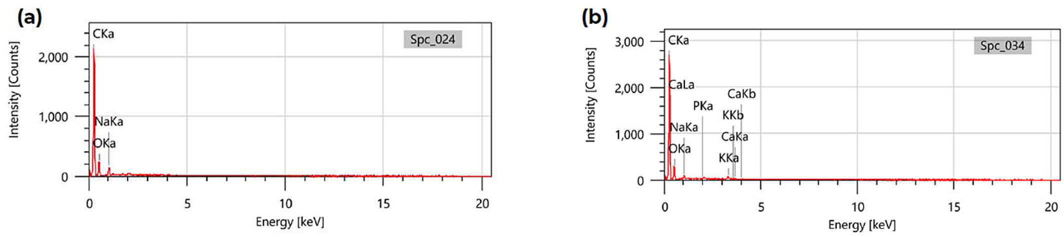


Figure 4. Scanning electron microscopy (SEM) images of bamboo biochar synthesized at 600 °C: (a) Biochar before adsorption (BB600), (b) Biochar after phosphate adsorption (BB600), (c) Chitosan-modified biochar before adsorption (BBM600), and (d) Chitosan-modified biochar after phosphate adsorption (BBM600)



Element	Mass %	Atom%
C	74.01 ± 0.34	79.67 ±0.37
O	23.23 ± 0.58	18.78 ±0.47
Na	2.76 ± 0.12	1.55 ±0.07
P	0.02 ± 0.03	0.01 ±0.01

Element	Mass %	Atom%
C	73.86 ± 0.31	79.79 ± 0.33
O	23.35 ± 0.53	18.94 ± 0.43
Na	1.45 ± 0.08	0.82 ± 0.05
P	0.14 ± 0.03	0.06 ± 0.01

Figure 5. Elemental composition analysis by energy-dispersive x-ray spectroscopy (EDS/EDX) of (a) bamboo biochar (BB) and (b) chitosan-modified bamboo biochar (BBM) after phosphate adsorption

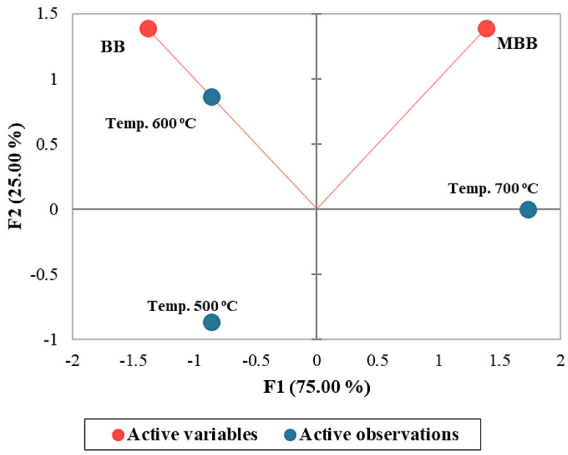


Figure 6. Principal component analysis (PCA) biplot showing the relationship between biochar types (BB, MBB) and synthesis temperatures (500, 600, 700 °C)

most influential principal component in differentiating the data. Conversely, the F2 axis explained 25.00% of the variance, serving as a supplementary component for further differentiation.

An examination of the variable positions in the graph (red dots) revealed that the BB and MBB variables were located on opposite sides of the F1 axis. BB exhibited a high negative Factor Loading on the F1 axis, while MBB showed a high positive loading. This configuration clearly indicates a strong negative correlation between the two variables along the F1 dimension. In essence, the prominent adsorption properties of BB tended to be inversely related to the adsorption properties of MBB. Furthermore, the distribution of the experimental observation points (blue dots) distinctly highlighted the influence of varying temperatures. The experiment conducted at 600 °C was positioned close to BB, suggesting that at this temperature, the original adsorption properties of the biochar were largely retained. In contrast, the experiment at 700 °C was notably positioned near MBB, demonstrating that treatment at 700 °C effectively transformed the biochar's properties towards that characteristic of MBB. For the experiment at 500 °C, its position was considerably distant from both BB and MBB, particularly along the F2 axis. This indicates that at this temperature, the adsorption properties of the biochar might undergo a distinct alteration compared to higher temperatures. In summary, the analytical results demonstrate that temperature plays a crucial role in modifying the adsorption properties of biochar. Specifically, treatment at 700 °C promoted the formation of biochar with properties characteristic of MBB. Conversely, 600 °C largely preserved the adsorption characteristics of BB. The 500 °C treatment represented a transition phase that may yield distinct properties.

The Dendrogram analysis, a hierarchical clustering technique used to illustrate relationships between variables or data, was employed here to group biochar synthesis temperatures (500 °C, 600 °C, and 700 °C) based on their dissimilarity values. As shown in Figure 7, this dissimilarity reflects the overall differences in the physicochemical properties of the biochar produced at these temperatures. The analysis reveals two distinct main clusters that differ significantly. The first cluster (C1) comprises temperatures 500 °C and 600 °C, showing a relatively low dissimilarity level (approximately 1.5 on the Y-axis). This close grouping clearly indicates that biochar synthesized at both 500 °C and 600 °C possesses highly similar fundamental characteristics and properties concerning factors affecting

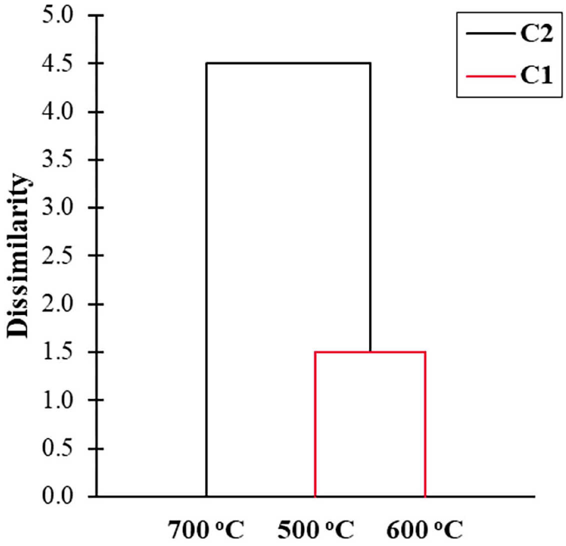


Figure 7. Dendrogram illustrating the hierarchical clustering of biochar synthesis temperatures based on dissimilarity

phosphate adsorption efficiency. This aligns well with experimental results demonstrating high phosphate adsorption efficiency from biochar at both these temperatures, with 600 °C yielding the highest performance. This consistency reflects an optimal temperature range for biochar production aimed at phosphate adsorption. In contrast, the 700 °C temperature (Cluster C2) exhibits significantly different behavior, being grouped with Cluster C1 at a much higher dissimilarity level (approximately 4.5 on the Y-axis). This substantial increase in dissimilarity clearly indicates that biochar synthesized at 700 °C possesses distinctly different and profoundly altered properties compared to biochar synthesized at 500 °C and 600 °C. This change in properties can be attributed to factors occurring at high temperatures, such as increased thermal stability and intensified hydrophobicity, as well as the potential for pore structure collapse. All these factors negatively impact phosphate adsorption efficiency. This clear statistical separation further reinforces the previous conclusion that increasing the pyrolysis temperature beyond an optimal point (e.g., above 650 °C) leads to changes in biochar properties that significantly reduce its phosphate adsorption capacity. Therefore, this Dendrogram serves as a powerful statistical tool that visually confirms and supports the experimental findings, demonstrating that biochar properties vary systematically with pyrolysis temperature and can be clearly divided into groups with distinct adsorption behaviors.

CONCLUSIONS

This study investigated the potential of BB and chitosan-modified BBM for phosphate adsorption, emphasizing the influence of pyrolysis temperatures (500, 600, and 700 °C). Pyrolysis temperature was found to be crucial, with unmodified biochar at 600 °C showing optimal phosphate adsorption efficiency (15.62%). Notably, chitosan modification significantly enhanced adsorption across all temperatures, with BBM synthesized at 600 °C (BBM600) proving most effective, achieving approximately 17.7% efficiency and a capacity of 0.76 mg/g. This improvement is attributed to chitosan's amine groups, which increase active adsorption sites for phosphate. Material characterization via SEM confirmed successful chitosan coating and structural integrity, while observed surface alterations post-adsorption were consistent with phosphate retention. Statistical analyses (PCA and Dendrogram) further reinforced the strong correlation between pyrolysis temperature, biochar properties, and adsorption performance, clearly differentiating the superior adsorption of 500 °C and 600 °C biochars from those at 700 °C.

In conclusion, the modification of bamboo biochar with chitosan significantly enhances its phosphate adsorption capacity, with biochar synthesized at 600 °C proving to be the most effective material. Detailed characterization using various techniques confirmed the success of the modification and provided insights into the phosphate adsorption mechanism, offering strong evidence for the potential of chitosan-modified bamboo biochar as a highly efficient, environmentally friendly, and sustainable adsorbent for phosphate removal from aqueous solutions, representing a promising approach for managing water pollution problems. While this study successfully demonstrated the potential of chitosan-modified bamboo biochar as an efficient adsorbent for phosphorus removal, further research is warranted to comprehensively evaluate its long-term stability, regeneration capabilities, and reusability over multiple adsorption-desorption cycles, which are critical factors for practical and sustainable application in real-world wastewater treatment systems.

Acknowledgements

This research was financially supported by (i) Suranaree University of Technology (SUT), (ii) Thailand Science Research and Innovation

(TSRI), and (iii) National Science, Research and Innovation Fund (NSRF) (Project ID: NRIIS 204169). The authors express their sincere gratitude to the Research, Innovation and Academic Services, Mahidol University Kanchanaburi Campus, for their invaluable support in providing access to the Scanning Electron Microscopy (SEM) instrument, which was essential for this study. Special appreciation is also extended to Mr. Natdania Somprasong, the laboratory scientist, for his dedicated service and assistance with the analysis.

REFERENCES

1. Al Masud M. A., Shin W. S., Sarker A., Septian A., Das K., Deepo D. M., Malafaia G. (2023). A critical review of sustainable application of biochar for green remediation: Research uncertainty and future directions. *Science of The Total Environment, 904*, 166813. https://doi.org/10.1016/j.scitotenv.2023.166813
2. Alves K. S., Guimarães T., de Carvalho Bittencout R., Gonçalves P. A. R., de Cássia Oliveira Carneiro A., Carvalho A. M. M. L., da Costa M. M. (2025). Bamboo-derived biochars: physicochemical properties and implications for soil fertility and sustainability. *Biomass Conversion and Biorefinery*, 1–21. https://doi.org/10.1007/s13399-025-06702-6
3. Bao Z., Shi C., Tu W., Li L., Li Q. (2022). Recent developments in modification of biochar and its application in soil pollution control and ecoregulation. *Environmental Pollution, 313*, 120184. https://doi.org/10.1016/j.envpol.2022.120184
4. Chin J. F., Heng Z. W., Teoh H. C., Chong W. C., Pang Y. L. (2022). Recent development of magnetic biochar crosslinked chitosan on heavy metal removal from wastewater–modification, application and mechanism. *Chemosphere, 291*, 133035. https://doi.org/10.1016/j.chemosphere.2021.133035
5. Díaz B., Sommer-Márquez A., Ordoñez P. E., Bastardo-González E., Ricaurte M., Navas-Cárdenas C. (2024). Synthesis methods, properties, and modifications of biochar-based materials for wastewater treatment: A review. *Resources, 13*(1), 8. https://doi.org/10.3390/resources13010008
6. Gao N., Du W., Zhang M., Ling G., Zhang P. (2022). Chitosan-modified biochar: Preparation, modifications, mechanisms and applications. *International Journal of Biological Macromolecules, 209*, 31–49. https://doi.org/10.1016/j.ijbiomac.2022.04.006
7. Gęca M., Khalil A. M., Tang M., Bhakta A. K., Snoussi Y., Nowicki P., Chehimi M. M. (2023). Surface treatment of biochar – methods, surface analysis and potential applications: a comprehensive review. *Surfaces, 6*(2), 179–213. https://doi.org/10.3390/surfaces6020013
8. He M., Xu Z., Hou D., Gao B., Cao X., Ok Y. S., Tsang D. C. (2022). Waste-derived biochar for water pollution control and sustainable development. *Nature Reviews Earth & Environment, 3*(7), 444-460. https://doi.org/10.1038/s43017-022-00306-8
9. Huang Q., Song S., Chen Z., Hu B., Chen J., Wang X. (2019). Biochar-based materials and their applications in removal of organic contaminants from wastewater: state-of-the-art review. *Biochar 1*: 45–73. https://doi.org/10.1007/s42773-019-00006-5
10. Joshi M., Bhatt D., Srivastava A. (2023). Enhanced adsorption efficiency through biochar modification: a comprehensive review. *Industrial & Engineering Chemistry Research, 62*(35), 13748–13761. https://doi.org/10.1021/acs.iecr.3c02368
11. Kadirvelu K., Thamaraiselvi K., Namasivayam C. (2001). Removal of heavy metals from industrial wastewaters by adsorption onto activated carbon prepared from an agricultural solid waste. *Bioresource technology, 76*(1), 63–65. https://doi.org/10.1016/S0960-8524(00)00072-9
12. Kalderis D., Seifi A., Trang T. K., Tsubota T., Anastopoulos I., Manariotis I.,..., Khataee A. (2023). Bamboo-derived adsorbents for environmental remediation: A review of recent progress. *Environmental Research, 224*, 115533. https://doi.org/10.1016/j.envres.2023.115533
13. Kyriakopoulos G. L., Zamparas M., Kapsalis V. C., Kalavrouziotis I. K. (2022). Eutrophication control: the shift to invasive methods managing the internal nutrient loads. A bibliometric analysis. *Desalination and Water Treatment, 267*, 177–185. https://doi.org/10.5004/dwt.2022.28708
14. Li L., Chen Q., Zhao C., Guo B., Xu X., Liu T., Zhao L. (2022). A novel chitosan modified magnesium impregnated corn straw biochar for ammonium and phosphate removal from simulated livestock wastewater. *Environmental Technology & Innovation, 26*, 102519. https://doi.org/10.1016/j.eti.2022.102519
15. Liang L., Xi F., Tan W., Meng X., Hu B., Wang X. (2021). Review of organic and inorganic pollutants removal by biochar and biochar-based composites. *Biochar, 3*, 255–281. https://doi.org/10.1007/s42773-021-00101-6
16. Liu C., Zhang H. X. (2022). Modified-biochar adsorbents (MBAs) for heavy-metal ions adsorption: A critical review. *Journal of Environmental Chemical Engineering, 10*(2), 107393. https://doi.org/10.1016/j.jece.2022.107393
17. Lou Z., Zheng Z., Yan N., Jiang X., Zhang X., Chen S.,..., Xu L. (2023). Modification and application of bamboo-based materials: a review—Part II: application of bamboo-based materials. *Forests, 14*(11), 2266. https://doi.org/10.3390/f14112266

18. Manyatshe A., Cele Z. E., Balogun M. O., Nkambule T. T., Msagati T. A. (2022). Chitosan modified sugarcane bagasse biochar for the adsorption of inorganic phosphate ions from aqueous solution. *Journal of Environmental Chemical Engineering, 10*(5), 108243. https://doi.org/10.1016/j.jece.2022.108243
19. Palansooriya K. N., Kim S., Igalavithana A. D., Hashimoto Y., Choi Y. E., Mukhopadhyay R.,..., Ok Y. S. (2021). Fe (III) loaded chitosan-biochar composite fibers for the removal of phosphate from water. *Journal of hazardous materials, 415*, 125464. https://doi.org/10.1016/j.jhazmat.2021.125464
20. Parasana N., Shah M., Unnarkat A. (2022). Recent advances in developing innovative sorbents for phosphorus removal—perspective and opportunities. *Environmental Science and Pollution Research*, *29*(26), 38985–39016. https://doi.org/10.1007/s11356-022-19662-5
21. Perera H. M., Rajapaksha A. U., Liyanage S., Ekanayake A., Selvasembian R., Daverey A., Vithanage M. (2023). Enhanced adsorptive removal of hexavalent chromium in aqueous media using chitosan-modified biochar: Synthesis, sorption mechanism, and reusability. *Environmental Research, 231*, 115982. https://doi.org/10.1016/j.envres.2023.115982
22. Priya E., Kumar S., Verma C., Sarkar S., Maji P. K. (2022). A comprehensive review on technological advances of adsorption for removing nitrate and phosphate from waste water. *Journal of Water Process Engineering, 49*, 103159. https://doi.org/10.1016/j.jwpe.2022.103159
23. Rangabhashiyam S., Balasubramanian P. J. I. C. (2019). The potential of lignocellulosic biomass precursors for biochar production: performance, mechanism and wastewater application-a review. *Industrial Crops and Products, 128*, 405–423. https://doi.org/10.1016/j.indcrop.2018.11.041
24. Tomczyk A., Sokołowska Z., Boguta P. (2020). Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. *Reviews in Environmental Science and Bio/Technology, 19*(1), 191-215. https://doi.org/10.1007/s11157-020-09523-3
25. Trivedi Y., Sharma M., Mishra R. K., Sharma A., Joshi J., Gupta A. B.,..., Vuppaladadiyamd A. K. (2025). Biochar potential for pollutant removal during wastewater treatment: A comprehensive review of separation mechanisms, technological integration, and process analysis. *Desalination,* 118509. https://doi.org/10.1016/j.desal.2024.118509
26. Usman M. O., Aturagaba G., Ntale M., Nyakairu G. W. (2022). A review of adsorption techniques for removal of phosphates from wastewater. *Water Science & Technology, 86*(12), 3113–3132. https://doi.org/10.2166/wst.2022.382
27. Witek-Krowiak A., Gorazda K., Szopa D., Trzaska K., Moustakas K., Chojnacka K. (2022). Phosphorus recovery from wastewater and bio-based waste: an overview. *Bioengineered, 13*, 13474–13506. https://doi.org/10.1080/21655979.2022.2077894
28. Wujcicki Ł., Kluczka J. (2023). Recovery of phosphate (V) ions from water and wastewater using chitosan-based sorbents modified—a literature review. *International Journal of Molecular Sciences, 24*(15), 12060. https://doi.org/10.3390/ijms241512060
29. Xia Y., Zhang M., Tsang D. C., Geng N., Lu D., Zhu L.,..., Ok Y. S. (2020). Recent advances in control technologies for non-point source pollution with nitrogen and phosphorous from agricultural runoff: current practices and future prospects. *Applied Biological Chemistry, 63*, 1–13. https://doi.org/10.1186/s13765-020-0493-6
30. Zhang X., Sun S., Han X., Liu H., Shu S. (2025). Phosphorus recovery from urban wastewater treatment in China: Current status, future potential and a roadmap for sustainable development. *Journal of Water Process Engineering, 69*, 106806. https://doi.org/10.1016/j.jwpe.2024.106806
31. Zhang X., Zhao B., Liu H., Zhao Y., Li L. (2022). Effects of pyrolysis temperature on biochar's characteristics and speciation and environmental risks of heavy metals in sewage sludge biochars. *Environmental Technology & Innovation, 26*, 102288. https://doi.org/10.1016/j.eti.2022.102288
32. Zhou Y., Gao B., Zimmerman A. R., Fang J., Sun Y., Cao X. (2013). Sorption of heavy metals on chitosan-modified biochars and its biological effects. *Chemical engineering journal, 231*, 512–518. https://doi.org/10.1016/j.cej.2013.07.036