*Frontiers in Water and Environment* 10, Issue 1 (2026) 13-32

Frontiers in Water and Environment

Journal homepage:
https://karyailham.com.my/index.php/fwe/index
ISSN: 2785-9029

# A Short Review: Phosphorus-Based Compounds Removal using Biomass-Derived Activated Carbon in Domestic Wastewater Treatment

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**ARTICLE INFO**

***Article history:***
Received 16 January 2026
Received in revised form 28 February 2026
Accepted 1 April 2026
Available online 28 April 2026

***Keywords:***

Adsorption; phosphorus-based compounds removal; activated carbon; domestic wastewater treatment, technologies for phosphorus removal

**ABSTRACT**

Phosphorus (P) is a finite yet essential nutrient that plays a critical role in plant growth and ecosystem sustainability. However, excessive discharge of P into aquatic environments leads to eutrophication, posing significant environmental challenges. Despite advances in wastewater treatment, efficient P removal from domestic wastewater remains complex due to its diverse chemical forms and interactions in aqueous systems. Conventional biological P removal processes typically require multiple treatment stages, resulting in operational complexity, large footprints, and extended hydraulic retention times that may compromise overall efficiency. Adsorption using activated carbon has emerged as a promising alternative owing to its operational simplicity, effectiveness, and cost efficiency. Recent research trends have shifted from coal-based activated carbon, derived from non-renewable resources, toward more sustainable and economically viable biomass-derived activated carbon. Nevertheless, comprehensive evaluations specifically addressing P removal and recovery performance using activated carbon synthesized from various biomass precursors remain limited. This review critically examines recent developments in P adsorption employing biomass waste-derived activated carbon. The performance of different biomass precursors is comparatively analysed in terms of adsorption capacity, removal efficiency, and operational parameters. Key findings are systematically tabulated to facilitate direct comparison and identify research trends and limitations. By synthesizing current knowledge, this work highlights the potential of biomass-derived activated carbon as a sustainable and environmentally responsible strategy for phosphorus removal and recovery, contributing to the advancement of resilient wastewater treatment systems.

## 1. Introduction

Domestic wastewater treatment plays a critical role in protecting water resources by removing contaminants from household and small-scale commercial activities businesses to make it safe for release back into the environment. This wastewater typically originates from kitchen sinks, showers,

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toilets, laundries and other domestic sources [1], and can be classified into yellow water (e.g., urine), brown water (e.g., manure and flush water), black water (e.g., urine, manure, bacterial activity), and greywater (e.g., water from kitchen sinks, toilets) based on its composition. Among the various pollutants present, phosphorus (P) remains one of the major challenges in domestic wastewater treatment, due to its complexity and varying compositions (e.g., condensed phosphate, orthophosphate, organic phosphate) in wastewater [2,3].

In domestic wastewater, P primarily originates from human manure, food residues and phosphate-based detergents and cleaning products, which contributes to the high P amounts [3]. Many household detergents and cleaning agents would contain phosphates, which are used to soften water and improve cleaning efficiency. Additionally, food waste and residues from cooking which contain natural phosphorus also contributed to this when rinsed down to the drain. Human excretion waste is also a significant source, as phosphorus is an essential nutrient in the diet and can be presented in food such as meats and dairy products which were then be excreted in urine and manures. P pollution is a critical environmental issue in domestic wastewater treatment, as its excess presence could lead to eutrophication, degrading water quality and dangers aquatic ecosystems.

The abundance of P which is essential nutrient for plant growth, could cause eutrophication where algae bloom and blocks sunlight and oxygen reaching water. Other than that, the microorganisms in the water would use up the remaining oxygen to break down any decaying matter, which cause oxygen lacking thus suffocating aquatic life due to insufficient oxygen. Thus, effective P removal from domestic wastewater has become a global priority with various technologies being explored. To this date, there are several technologies implemented in the domestic wastewater treatment for the P–based, which are based on biological, physical, chemical, physicochemical and hybrid treatment, which are tabulated in Table 1.

### *1.1 Biological Treatment*

Biological treatment in wastewater usually involves the use of living microbial like bacteria, algae, or fungi to remove contaminants by P assimilation [4]. The treatment method mimics the natural process of water purification occur in water bodies (i.e., rivers, lakes, wetlands), where these microbials will grow by consuming and breaking down the organic pollutants, converting them into harmless substances like carbon dioxide, water, and biomass (sludge).

Assimilation of P by bacteria depends on microbial group, particularly known as Phosphorus-accumulating organisms (PAO), where these organisms would store phosphate within PAO cell as intracellular poly-phosphate (Poly-P), hence resulting to phosphorus removal from liquid phase in waste activated sludge [5]. Bunce *et al.,* [6] reported that the use of PAOs such as *Candidatus Accumulibacter Phosphatis* (Accumulibacter) for enhanced biological phosphate removal (EBPR), could improve the luxury P-uptake however, its biochemical mechanism is not yet fully understood and required optimization for its operating conditions to promote the PAO’s growth and proliferation.

Other than that, P assimilation by microalgae also demonstrated the ability to proliferate and reduce P concentrations in wastewater, close to 1 mgTP/L [4],. Bunce *et al.,*[6] stated that the most common microalgae found in the natural ecosystem are the green microalgae *Scenedesmus* species and *Chlorella* species. Their mechanisms are based on absorbing P (orthophosphate) excessively, beyond the growth’s needs, and being stored as Poly-P granules inside microalgae. However, total P removal efficiency using microalgae would be only about 36 to 41%, as mentioned in study by Sukacova *et.al.,* [7] under solar radiation; 12h sunlight and 12h night where optimization is required to increase P removal efficiency to achieve 97%, under continuous 24h artificial lighting, which would need additional cost for energy consumption.

P assimilation by fungi, such as *M. circinelloides* also shown to be an option as it is much easier to harvest compare than bacteria, as it could form a complex network called as mycelium structure that grows by extending at the tips [4]. P will be accumulated in poly-P granules hence removing the contaminant from wastewater. Yet, P removal efficiency using filamentous fungi could achieve up to 53% only [4], where pre-treatment or combination with other process are necessary for effectiveness.

Apart from that, the traditional removal of the P-based compounds via biological treatment requires multiple stages of biological treatment, which consists of a combination of anaerobic, anoxic and aerobic conditions. There are several technologies use this biological treatment, as stated in Table 1 such as EBPR and membrane bioreactor (MBR) as reported in studies by Bunce *et al.*, [6] and Long *et al.,* [8]. Although these technologies are commonly implemented in the industry, yet it requires strict operational control, a large plant footprint, longer duration of the treatment and facing continuous membrane fouling issue [5,9].

### *1.2 Physical Treatment*

Physical treatment like membrane filtration, remove contaminants without altering their chemical composition and usually relies on physical mechanism, to remove large and settleable solids or particles [5]. For P removal, technology using physical mechanism is such as reverse osmosis (RO) or nanofiltration (NF), which is a membrane filtration technique that use application of hydraulic pressure to drive water molecules pass through semipermeable membrane [10]. The contaminants will be retained in the concentrate stream as they do not pass through the membrane filtration, which is best used for dissolved P. Aside from reverse osmosis and nanofiltration, other available technologies are microfiltration (MF) and ultrafiltration (UF), yet the removal efficiencies are lower than RO and NF [11]. It was reported that the removal of total phosphorus was 97%, 26% and 34 % for NF, UF and MF, respectively. These membranes are easily affected by pH variation, where it needs to be controlled in range of 6.0 to 8.0 in order to minimize inorganic scaling and maximize shelf life [12]. Additionally, RO technology would be too expensive due to accumulation of foulants that requires frequent membrane maintenance [13] or inefficient in removal of P, where it would remove only 10% of the Total phosphorus (TP) [14].

### *1.3 Chemical Treatment*

Chemical treatment uses chemicals or processes to either precipitate contaminants, adsorb it or convert it into a form that can be easily separated from water. This method involves chemical reactions like oxidation, reduction, precipitation or neutralization. Chemicals commonly used for P precipitation predominantly includes aluminium salts, iron salts, and calcium salts [12,15]. Study by Reif *et al.,* [16] suggested that these salts are effective in precipitating dissolved P components, assisting in larger insoluble particles formation and agglomeration for easier removal through sedimentation or filtration. While the chemical precipitation method for P removal is stable, reliable, and efficient, it comes with a high economic cost. Additionally, it needs pH adjustment and generates a large amount of chemical sludge with a complex composition [17,18], making it difficult to manage and prone to causing secondary pollution. This aspect is unfavourable to achieve P recovery and utilization of resource [19].

### *1.4 Physicochemical Treatment*

Physicochemical treatments in wastewater involves the combination of physical and chemical methods to remove pollutants. These methods are particularly effective for treating wastewater containing particles that are difficult to remove through biological processes alone. It was reported in Y. Chen *et al.,* [5], the physicochemical treatment can be used for P removal in wastewater is using adsorption technique such as ion exchange and activated carbon, which offers simplicity of the operation. Adsorption method involves adding specific adsorbents to wastewater, where the active functional groups exist on adsorbent's surface, will form bonding with P to achieve removal [19]. However, the long-term sustainability of the aforementioned technologies has not been-well demonstrated.

Ion exchange for P removal practically uses electrostatic force of physical attraction between phosphate ion and the adsorbent, by exchanging it with other ions using specialized resins [4,20]. Suitable adsorbent materials with large surface area and possess active sites with neutrally or positively charged surface, would be selected. In this process, the wastewater flows through the anion exchange resin bed, and the process relies on physical contact between the resin and the phosphate ions in the water for the exchange to occur. The chemical reaction will occur at the resin surface, where phosphate ions in the wastewater are exchanged with anionic ions bound to the resin. The ion-exchange process has allowed P accumulation and recovery, presenting efficiencies above 90% [4,21,22]. However, ion exchange technology requires expensive chemical addition for recovery of phosphorus which makes its unfeasible for small scale or rural treatment works.

Meanwhile, adsorption using activated carbon offers better efficacy yet simple application in wastewater, owing to its highly porous material with a large surface area, which makes it effective at adsorbing a wide range of contaminants including phosphorus. In this treatment process, phosphate ions are attracted to active groups on the surface of the activated carbon, hence removes them from the wastewater [19]. Unlike chemical precipitation technology, adsorption using activated carbon does not require the addition of chemicals which reduces the cost and potential for chemical waste generation. From **Error! Reference source not found.**, the adsorption process using activated carbon is considered to be most effective at low phosphate concentration, easier to handle, cheaper plant operation and provides the ability of phosphate recovery after adsorption [2,23].

The research strategy used in this work is adapted from work by Wong *et al.*, [24] with modifications. This involved identification of relevant research works from the most recognized academic database such as Scopus, Science Direct and Google Scholar websites. The keywords used in initial search included different combinations of keywords such as "activated carbon" "biomass", "adsorption", "phosphorus" and "domestic wastewater treatment". The search results were then altered by title and abstract. Additional rules were also used in selection of research works for detailed analysis, including availability of abstract and full text. Considering that many review papers on domestic wastewater treatment via adsorption using activated carbon were published previously (summarized in Table 1), only the research works published from 2020 to 2025 are included in this review as an update to earlier reviews, although earlier works are also used to contextualize the work and to compare with recently developed adsorbents.

**Table 1**
Summary of recent reviews on phosphorus removal in wastewater using different technologies

| Treatment and process | Technology | Advantages | Disadvantages |
|---|---|---|---|
| Biological<br>(Bacteria assimilation) | Enhanced biological phosphate removal (EBPR) | -Cost effective and environmentally sustainable alternative to chemical treatment [6] | -Not fully reliable due to fluctuating performance, high dependence on skilled operators resulting in difficulty in process control [6]<br>-Local environment conditions affect efficacy rather than specific microbial communities [6]<br>-Less suitable for small scale at decentralized treatment plant [6]<br>-Need carbon addition as it affect PAO’s growth [4] |
| Biological<br>(Bacteria assimilation) | Conventional activated sludge treatment | -Low operation cost and low amount by-products produced,<br>achieved nearly complete P removal [25] | -Less effective at trace level, requires strict operation control [25] |
| Chemical<br>(Electrochemical) | Chemical precipitation | Reliable and widely accepted in phosphorus removal [2] | -P removal is proportional to mass of chemicals added, which could arise environmental problem [8]<br>-Have difficulty in sludge disposal and effluent neutralization [2] |
| Physical (Membrane filtration) | Reverse/direct osmosis | -Compact systems compared to other advanced treatment processes, making them suitable for limited space<br>-Suitable for dissolved phosphorus [4] | -Too expensive/ inefficient in removal of phosphorus, removing only 10% of the total P [25]<br>-Very small pore size of membranes causing cake layer, hence reduces water production rate [26] |
| Physical (Membrane filtration) | Microfiltration/ ultrafiltration | -Suitable for phosphorus with particle form less than 0.1µm, membrane rejection results in easily recoverable source of P [4] | -Sensitive to pH variation [4]<br>-Need to operate in pH of 6.0-8.0 to reduce inorganic scaling and to maximize shelf life [12]<br>-High cost of membrane filters and energy to operate [4] |
| Chemical (Chemical precipitation, chemical extraction) | Ion exchange column | -Phosphate ion ($PO_4^{3-}$) are reversibly interchanged between liquid wastewater and solid ion exchanger, | -Limitations in exchange capacity [19]<br>-Limited P removal in full scale due to requirement of |

| | | | |
|---|---|---|---|
| Physical (Ion exchange, Adsorption) or Physicochemical | | resulting in simultaneous P removal and recovery [6],<br>-P recovery efficiencies above 90% [21] | expensive chemical addition for its recovery [6]<br>-High energy consumption for electrodialysis process [4] |
| Chemical (Chemical precipitation)<br>Physical (Support adsorption, magnetic separation) or Physicochemical | Biofilter | -Easy to operate, does not require lot of energy consumption, does not produce sludge [4] | -Limited knowledge on magnetic separation up to this date [4] |
| Chemical (Chemical precipitation)<br>Physical (Adsorption) or Physicochemical | Activated carbon | -Effective and simple application, has a good P removal performance [2]<br>-Adsorbed phosphorus could be recovered [27]<br>-Reduce generation of subsequent sludge, offers low-cost operation [19] | Separation and recovery step of activated carbon is still costly and time consuming, thus limiting this technology application in industry [4] |
| Biological (Bacteria assimilation)<br>Chemical (Chemical precipitation, electrodialysis, electrochemical) or Hybrid | Microbial fuel cell | -Balanced system in energy and chemical dosage, pH (alkaline) can be raised without other addition of chemicals, contributes to pH adjustment for subsequent P precipitation, easy process where application of electrochemical method is used for P accumulation [4] | -Need chemical additions for high P recovery, high cost for chemical additions, need pH adjustment as it influences the material's precipitation formation [4] |
| Biological (Bacteria, macrophytes assimilation)<br>Chemical (Chemical extraction)<br>Physical (Support adsorption) or Hybrid | Constructed wetland | -Moderate P removal efficiencies can be achieved using natural materials i.e., zeolite, apatite and sand (45-80%), moderate to high P removal efficiencies can be achieved using waste materials i.e., steel, opoka (77%-99%) [4] | -Need natural materials modification to increase P adsorption such as acid treatment, pre-treatment of waste materials is crucial due to high alkalinity of ashes (pH 9.0 to 12.0) [4] |
| Biological (Bacteria, algae, fungi, organisms assimilation)<br>Chemical (Chemical extraction)<br>Physical (Membrane filtration) or Hybrid | Membrane bioreactors (MBR) | -High P removal performance [6]<br>-Produce higher quality effluent [28]<br>-Suitable for any size of treatment plant including small physical footprint [6] | -Relatively high capital and operating cost which limits wide applications of this technology [4]<br>-Continuous issue with membrane fouling hence, required frequent maintenance [6] |

To the best of the authors' knowledge, although biomass-derived activated carbon (AC) has increasingly attracted attention as a sustainable alternative for P removal, a systematic and comprehensive evaluation of its performance using different biomass precursors remains limited. Existing studies are often fragmented, focusing on specific biomass types or experimental conditions without providing a comparative assessment of adsorption efficiency and material properties. This lack of consolidated analysis hinders the identification of optimal biomass sources and the advancement of scalable applications. Therefore, this paper presents a comprehensive review of phosphorus removal through adsorption using activated carbon derived from various biomass wastes. The performance characteristics, adsorption capacities and influencing parameters are critically analysed and compared. By synthesizing current research findings, this review aims to provide clearer insights into the potential of biomass-derived activated carbon and to support the development of sustainable and resilient wastewater treatment strategies aligned with circular economy principles.

## 2. Activated Carbon

Activated carbon (AC) is a carbonaceous material or also referred as activated biochar, is produced through either a direct one step or a two-step process called carbonization and activation which need an initial carbon precursor before activation [29]. There are extensive variety of carbon sources that can be utilized in its production, making it a versatile material to be developed. AC is widely utilized due to its adjustable pore structure, high surface area and surface functionality, making it suitable for various applications, including water treatment [30].

However, using biomass as initial precursor for activated carbon has been widely studied as it aligns well with sustainability goals, provides economic advantages, and offers tailored performance for a wide range of applications, wherein the properties of activated carbon are strongly influenced by the nature of the biomass precursor used in its preparation. It represents an eco-friendly alternative to coal-based precursors as mentioned in Yong *et al.,* [31], making it a preferrable choice in many industries, especially in wastewater treatment.

### *2.1 Type of Biomass*

In general, biomass refers to any organic material derived from living or recently living organisms. There are several types of biomasses commonly being used as initial carbon precursors to produce activated carbon such as agricultural waste (i.e., palm kernel shells, corncobs and coconut shells), wood and sawdust, plant stems and fibres (i.e., bamboo) and animal-based biomass (i.e., bones and fish scales). Beside biomass, several non-biomass precursors such as coals, petroleum by-products, synthetic polymers, natural minerals (i.e., zeolites) and industrial wastes (i.e., sludge from wastewater treatment) are also being used for activated carbon development, especially when specific properties or performance characteristics are required. In addition to the nature of biomass source, the synthesis and activation method plays a decisive role in determining the physicochemical characteristics of the resulting activated carbon.

### *2.2 Synthesis of Activated Carbon from Biomass*

In general, biomass refers to any organic material derived from living or recently living organisms. There are several types of biomasses commonly being used as initial carbon precursors to produce activated carbon such as agricultural waste (i.e., palm kernel shells, corncobs and coconut shells), wood and sawdust, plant stems and fibres (i.e., bamboo) and animal-based biomass (i.e., bones and fish scales). Beside biomass, several non-biomass precursors such as coals, petroleum by-products, synthetic polymers, natural minerals (i.e., zeolites) and industrial wastes (i.e., sludge from wastewater treatment) are also being used for activated carbon development, especially when specific properties or performance characteristics are required.

To this date, commercial ACs used in wastewater treatment are produced from coconut shells, woods, straw waste, palm kernel shells and others (**Error! Reference source not found.**). ACs possess several desirable properties that enable its use in adsorption which are large surface area and porosity, together with surface chemistry that reacts with molecules with specific functional groups. However, as domestic wastewater treatment is less profitable compared to other industrial sectors, it is always preferable to reduce the cost involved in its treatment. Thus, the potential of biowaste to produce a low-cost adsorbent has been recognised since the last decade, and numerous studies have been conducted to determine the characteristics and efficiencies of ACs produced from various biomass waste in removal of phosphorus.

As shown in Figure 1 below, synthesis of ACs from biomass waste generally starts with pre-treatment of the sample, including washing, drying at 100 to $105^{0}$C and sieving to obtain small particles within a specific size range [24]. Then, followed by carbonization of biomass through thermal degradation where the precursor will be heated until certain temperature (600 to $1000^{0}$C) under dry inert atmosphere, to facilitate in elimination of volatile matters and moisture, thus leads to formation of porous biochar [30].

After carbonization process, the biochar obtained will be activated using physical or chemical method. Physical activation involves heating the biochar in high temperature (700 to $900^{0}$C) under inert atmosphere such as nitrogen gas ($N_2$), carbon dioxide ($CO_2$) or steam, to remove oxygen and hydrogen content, producing activated carbon with desired porosity [32]. Meanwhile, chemical activation uses addition of activating agents like acid, base and salts, to the biochar, followed by heating at 300 to $500^{0}$C to form a highly porous structure with high surface area [24]. These synthesis routes directly affect the adsorption capacity of biomass-derived activated carbon by tuning its surface area, pore structure, and surface functional groups.

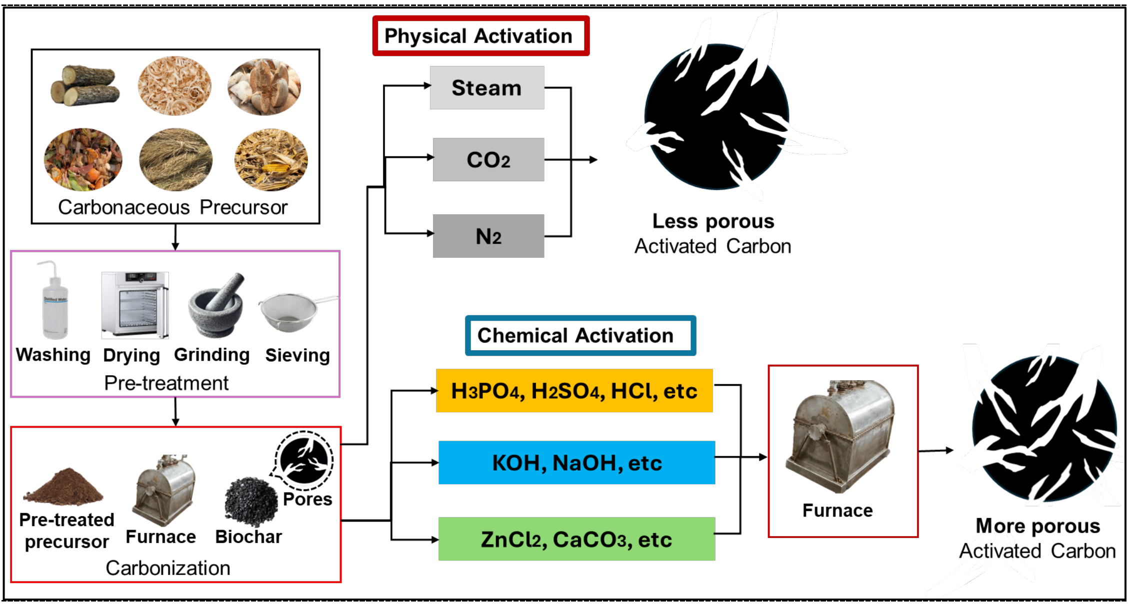

**Fig. 1.** Schematic diagram of synthesis routes for preparation of AC from various carbonaceous materials [33]

### *2.3 Adsorption Capacity of Biomass Derived AC's*

Adsorption capacity is widely employed as performance indicator for assessing efficacy of biomass-derived activated carbon in phosphorus removal applications. It refers to the amount of phosphorus could be absorbed per unit mass activated carbon and equip with quantitative measure of utilization of available adsorption sites. A higher adsorption capacity indicates a greater availability of active adsorption sites and reflects the efficiency of the activated carbon in treating phosphorus-contaminated wastewater. The adsorption capacity of biomass-derived activated carbon is strongly governed by its physicochemical properties, including surface area, pore structure, surface functional groups, and the presence of mineral or metal-based active sites. Reported adsorption capacities for phosphorus using biomass-derived activated carbon vary widely depending on biomass source, activation method, and experimental conditions.

Based on study by Waheed *et al.,* [34], to further evaluate the adsorption behaviour and underlying mechanisms between phosphorus species and activated carbon surfaces, adsorption isotherm (e.g. Langmuir and Freundlich) and kinetics model (e.g. Lagergren Pseudo first order and Pseudo second order reactions) are commonly applied.

### *2.3.1 Adsorption isotherm models*

In order to determine either adsorption on activated carbon is monolayer or multilayers, the experimental adsorption data were being analysed with different adsorption isotherm models such as Langmuir and Freundlich isotherm as discussed in the following sub section. The data that have good fit with Langmuir model would suggest monolayer adsorption where each adsorption site can hold only one adsorbate molecule [35]. Meanwhile, if the data fits well with Freundlich model, it suggests the heterogeneous adsorption that might involving both monolayer and multilayer adsorption [35].

Monolayer adsorption can be either physisorption or chemisorption as illustrated in Figure 2, depending on the nature of the interaction between the adsorbate and the adsorbent surface. Particularly, the physisorption process was determined by pore structure, whereas the chemisorption process was dominated by the functional groups [36]. Physisorption involves weak Van der Waals forces such as dipole-dipole or dispersion forces, where the adsorbate would attach to the pores without chemical binding in which typically leads to monolayer adsorption. However, due to weak Van der Waals forces also, it might cause the adsorbate molecules to attract each other thus favouring multilayer adsorption. Physisorption process is a reversible process as it only has weak van der Waals interactions between adsorbate and adsorbent surface.

For chemisorption process, it involves stronger chemical bonding (e.g., covalent, ionic or strong electrostatic interactions) between the adsorbate and the adsorbent surface. Once a molecule binds to a surface site via chemical bonding, the site will be occupied and would be unavailable for further adsorption. Thus, this process usually forms a monolayer adsorption. Chemisorption process is usually irreversible due to the strong chemical bonds between adsorbate and adsorbate surface, unlike physisorption process which involves weak Van der Waals attraction [19].

For maximum adsorption capacity, the adsorption would reach a clear plateau concentration, suggesting the monolayer adsorption as all available adsorption sites are occupied and no further adsorption occurs beyond the monolayer. This is known as Langmuir saturation. Meanwhile, if there is no saturation plateau, the adsorption capacity would increase continuously with concentration without a clear saturation point which indicate to multilayer adsorption, as additional layers of adsorbate are forming.

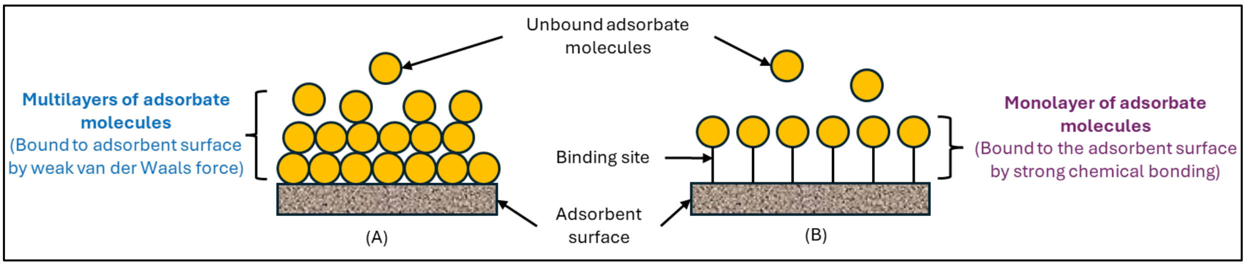

**Fig. 2.** Type of interaction between adsorbate molecules and adsorbent surface via (A) physisorption; (B) chemisorption

### *2.3.1.1 Langmuir model*

Langmuir isotherm model is the oldest and commonly used in studies related to adsorption mechanism. This model assumes adsorption as a homogenous process in which adsorbate is adsorbed in the form of a monolayer onto adsorbent, with adsorption taking place at fixed number of adsorption sites due to all the adsorbate molecules possess equal enthalpies and activation energies [35]. Eq. (1) given is non-linear form of the Langmuir isotherm model.

$$q_e = \frac{Q_m K_L C_e}{1 + K_L C_e} \tag{1}$$

where the $q_e$ is amount of the adsorbate absorbed per unit of the adsorbent (mg/g), $Q_m$ is maximum adsorption capacity (mg/g), $K_L$ is Langmuir constant at equilibrium concentration (L/mg) and $C_e$ is concentration of the adsorbate at equilibrium (mg/L).

### *2.3.1.2 Freundlich model*

Freundlich isotherm is applied based on multilayer adsorption on heterogeneous surface and may be expressed in the following Eq. (2) [37]. Unlike Langmuir isotherm which assumes monolayer adsorption, Freundlich model has non-limiting adsorption and does not have a saturation point, where the adsorption can continue increasing as Ce increase, forming multilayer adsorption.

$$\log q_e = \log K_F + \frac{1}{n} \log C_e \tag{2}$$

where the $q_e$ is amount of the adsorbate absorbed per unit of the adsorbent (mg/g), $K_F$ is Freundlich constant at equilibrium concentration (L/mg), (1/n) is dimensionless factor indicating the intensity of adsorption and $C_e$ is concentration of the adsorbate at equilibrium (mg/L).

For biomass-derived AC, adsorption isotherm studies have demonstrated that phosphorus uptake is often better described by the Freundlich model, reflecting the heterogeneous nature of surface functional groups and pore structures introduced during chemical or physical activation. While adsorption isotherm models describe equilibrium adsorption behaviour, kinetic models offer insight into the rate-controlling steps and adsorption mechanisms.

### *2.3.2 Adsorption kinetics models*

Various kinetic models are employed to the adsorption data to get deeper understanding of the performance and mechanism of adsorption. Based on study by Waheed *et al.,* [34], kinetics studies also helps in determining the time required for completion of the adsorption process and the rate of solute uptake. Several adsorption models have been developed over the past years, which have broadly been classified into two categories such as adsorption reaction models and adsorption diffusion models.

In general, the diffusion models work through three consecutive steps where the first is film diffusion, in which diffusion occurs through the liquid film surrounding the adsorbent particles. Secondly, intra-particle diffusion in which diffusion occurs in the liquid contained in the pores or along the walls of the adsorbent. Thirdly, the mass action where adsorption and desorption occur between the adsorbate and active sites of the adsorbent surface. In contrast to the diffusion models, the adsorption reaction models depend on the adsorption process as a whole without depending on the afore-mentioned steps. Various adsorption kinetics models, typically Lagergren Pseudo first order and Pseudo second order model have been reviewed in study by Waheed et al., [35].

### *2.3.2.1 Pseudo first order model*

Pseudo first order model is represented by following Eq. (3).

$$\log(q_e - q_t) = \log q_e - \frac{k_1 t}{2.303} \tag{3}$$

where the $q_e$ is equilibrium adsorption capacity (mg/g), $q_t$ is maximum adsorption capacity at t, min (mg/g) and $k_1$ is Pseudo first order rate constant.

### *2.3.2.2 Pseudo second order model*

Meanwhile, Lagergren Pseudo second order kinetic model is represented by the following Eq. (4).

$$\frac{t}{q_t} = \frac{1}{k_2 {q_e}^2} + \frac{t}{q_e} \tag{4}$$

where the $q_e$ is equilibrium adsorption capacity (mg/g), $q_t$ is maximum adsorption capacity at t, min (mg/g) and $k_2$ is Pseudo second order rate constant

As reported in study by Waheed *et al.*, [35], the fitting of a particular kinetic model depends on the value of regression coefficient, $R^2$ and comparison of $q_{e,\text{ calculated}}$ and $q_{e,\text{experimental}}$ where the best-fitted model has the value of $R^2$ reaching to unity with closely resembling values of $q_{e,\text{ calculated}}$ and $q_{e,\text{experimental}}$. Kinetic studies of phosphorus adsorption onto biomass-derived AC typically fit the pseudo second order model where chemisorption plays a significant role and it gives more accurate estimation of equilibrium adsorption capacity ($q_e$) compared to the pseudo first order model [38].

### *2.4 Removal of Phosphorus using Biomass-derived AC*

ACs are proven to be effective in removal of various challenging pollutants from aqueous solutions, including phosphorus. This paper only includes some outstanding publications on AC from biomass for phosphorus removal from simulated and real domestic wastewater, as tabulated in Table 2. It summarizes the important aspects of the latest research works, including type of biomass waste used as initial precursor, preparation steps of the AC, and their adsorption capacity. From Table 2, biomass waste that is impregnated with metal such as Fe, Mg, Ca could develop activated carbon with high adsorption capacity (149.27 to 221.89 mg/g) which would indicate to high phosphorus removal efficiency. Meanwhile, activated carbon synthesize from salts and chemicals have lower adsorption capacity (39 to 29.37 mg/g), resulting in lower phosphorus removal efficiency.

**Table 2**
Phosphorus adsorption on biomass-derived activated carbon

| Precursor | Adsorption Capacity, $Q_e$[a] | References |
|---|---|---|
| Peanut shells ($CaCO_3$ activation, $800^oC$) | 168.2 | [39] |
| Agricultural straw waste ($Al(NO_3)_3.9H_2O$ activation) | 89.37 | [40] |
| Coconut shell carbon fibre ($Mg(NO_3)_2{\cdot}6H_2O$ & $C_6H_{12}N_4$ activation) | 60.39 | [41] |
| Starch (CaO & $AgNO_3$ activation, ) | 77.4 | [42] |
| Pine bark | 4.02 | [43] |
| Agricultural crab shells (Load Fe) | 149.27 | [44] |
| Agricultural tangerine peel (Load Ca, Zn) | 52.96 | [45] |
| Agricultural rice straw (Load Ca, La) | 84.72 | [46] |
| Agricultural corn stalk (Load Mg) | 221.89 | [47] |
| Industrial fly ash (Mesontobermullite) | 221.2 | [48] |
| Industrial cinder (Load Mg, La) | 39.22 | [49] |
| Industrial slag (Wet ball mill pyrolysis) | 39 | [50] |

[a] Unit of $Q_e$ is mg/g unless stated otherwise

The synthesis route and activation conditions employed in converting biomass into activated carbon would significantly influence its surface area, pore structure, and surface functional groups [51], which determines its adsorption capacity for P-based compounds. Specifically, a higher surface area, provides more active sites for phosphate binding, while the presence of oxygen-containing functional groups enhances electrostatic interactions with P-based compounds [19]. Consequently, variations in precursor type and activation method can result in remarkably different adsorption efficiencies. Thus, understanding the influence of these properties is essential, as they directly govern the adsorption performance of activated carbon. The following sections will be discussed on key factors affecting adsorption performance using activated carbon in domestic wastewater treatment.

## 3. Factors Affecting Phosphorus Adsorption Performance onto ACs

The key criteria for efficacy of adsorption method lies in producing a good adsorbent material with strong adsorption effect and minimum risk of secondary pollution to environment [19]. A good adsorbent should not create another pollution problem although it will remove phosphorus from wastewater effectively. The main factors to the success of adsorption method can be seen as in **Error! Reference source not found.**, which are surface area, pore structure, surface chemistry and activation pathways. These factors collectively enhance the adsorption efficiency of activated carbon for removing phosphorus-based compounds in domestic wastewater treatment which will be discussed in following section.

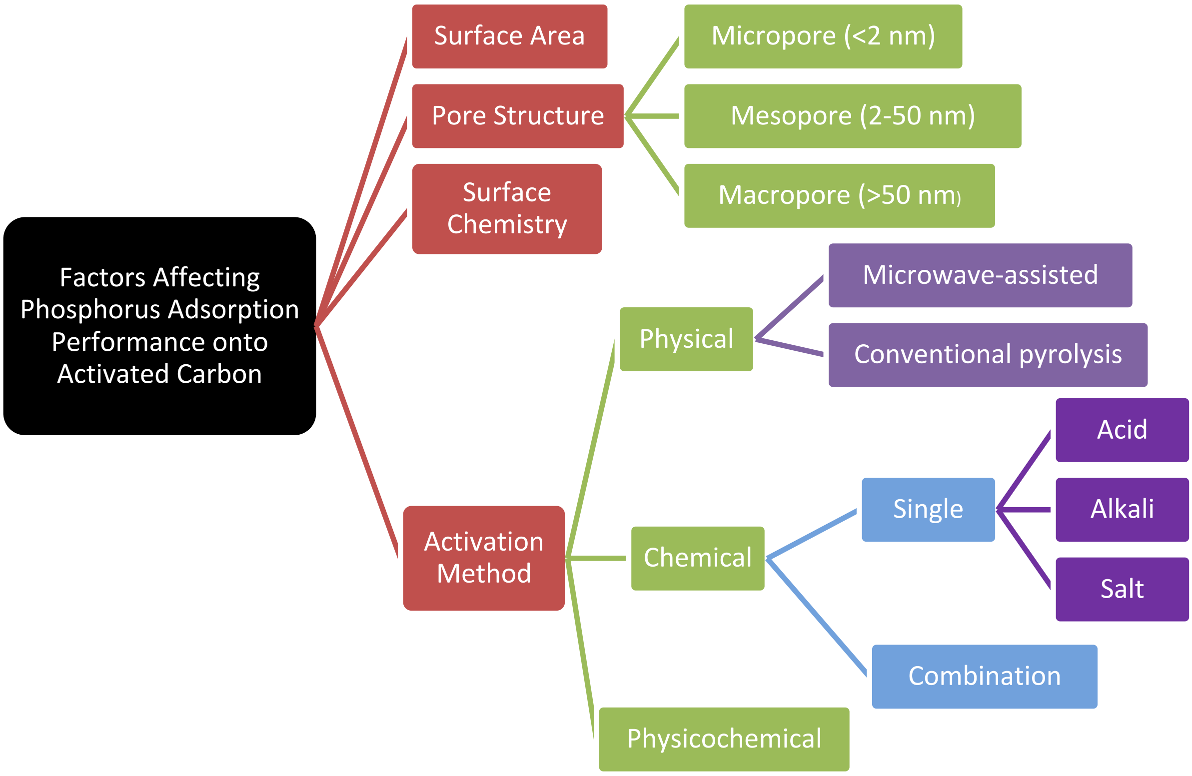

**Fig. 2.** Factors affecting phosphorus adsorption performance onto ACs

### *3.1 Surface Area*

A high surface area of available adsorption sites at activated carbon is often associated with a good adsorption performance [30]. Larger surface area typically imparts more adsorption sites, however, surface chemistry would also influence phosphate uptake. Different types of AC derived from diverse biomass as precursor, possess distinct characteristics like surface areas, leading to varied adsorption effects on phosphorus in water. Generally, activated carbons with surface areas ranging from 500 $m^2/g$ to 3,000 $m^2/g$ are considered to have good adsorption properties [52].

Yuan *et al.,* [40], synthesized AC from agricultural straw waste (a low-carbon biomass precursor) using Aluminium nitrate nonahydrate, $Al(NO_3)_3.9H_2O$, obtained surface area of 42 $m^2/g$ with 89.37 mg P/g adsorption capacity, while by using coconut shell carbon fibre (a high-carbon biomass precursor) impregnated with Magnesium nitrate hexahydrate, $Mg(NO_3)_2·6H_2O$ and hexamethylenetetramine, $C_6H_{12}N_4$, a lower surface area (38.97 $m^2/g$) and lower adsorption capacity is obtained (60.83 mg P/g). Study from Y. Xu *et al.,* [39] demonstrating that activated carbon produced from peanut shells (rich carbon source) and oyster shells (calcium carbonate source) via co-pyrolysis (800$^0$C), shown remarkable P adsorption capacity (168.2 mg P/g) with high surface area (127.25 $m^2/g$). The analysis suggested that impregnation with metal species (calcium), could produce AC with high surface area, resulting in higher adsorption capacity. There will be greater number of active sites available for specific interaction with phosphate species due to metal-based functional sites.

Study by Hai *et al.,* [30] suggested that biomass rich in lignin such as pistachio shells (78% volatile matter and 1.8% ash content), manifest a higher surface area (1640 $m^2/g$) rather than saffron petals and orange peel, 300 $m^2/g$ and 870 $m^2/g$ respectively. Nevertheless, oxygen content in biomass as precursor should be considered for surface area optimization as biomass with high hydrogen and low oxygen content could exhibit lower surface area [30].

### *3.2 Pore Structure*

Activated carbon with well-developed pore structure generally exhibit a good adsorption performance, whilst surface chemistry and functional groups also play a critical role. Based on study by Hoseinzadeh Hesas *et al.*, [53], there are three types of pores which are micropores (molecule size less than 2 nm), mesopores (molecule size ranging from 2 to 50 nm) and macropores (molecule size is larger than 50 nm). In order to ensure efficient diffusion and adsorption of phosphorus molecules, a high porosity with uniform pore size distribution would be required. Factors that can affect the pore structure are influence by type of biomass as raw materials and pyrolysis temperature during activation [30].

Fan *et al.,* [54] demonstrated a study on obtaining AC from cellulose that undergo pre-treatment with $H_3PO_4$, via different activation temperature (200-700$^oC$) where the formation of mesopores and micropores on AC can be obtained at temperature as low as 200$^oC$ and further increase of temperature would enhanced cracking of volatile matters, thus resulting in mesopores formation (probably via micropores merge) and larger pore diameter. However, higher temperature inevitably could led to pore collapse but higher surface area [55]. Yuan et al. (2021), synthesized AC from agricultural straw waste using aluminium nitrate nonahydrate, $Al(NO_3)_3.9H_2O$, obtained pore size of 2.56 nm with 89.37 mg P/g adsorption capacity, while Y. Xu *et al.,* [39] demonstrating that activated carbon produced from peanut shells (carbon rich source) and oyster shells (calcium carbonate source) via co-pyrolysis (800$^oC$), shown remarkable P adsorption capacity (168.2 mg P/g) with high pore size (12.28 nm).

From the studies, generally as the pore size increase, the adsorption capacity would be increased. The combination of mesopores and micropores would allow efficient phosphate ions adsorption onto activated carbon, as they can accommodate the phosphate ions to fit into micropores while mesopores site would facilitate the movement of phosphate ions to the micropores site. Meanwhile, macropores are generally too large for phosphate adsorption, as they may not provide the required electrostatic interactions or surface area needed for significant ion binding. Therefore, an optimal mix of pore sizes would enhance the overall adsorption performance.

### *3.3 Surface Chemistry*

Adsorption of contaminants by activated carbon is closely associated with surface functional groups [56]. The surface acidity or basicity can be tailored during activation to optimize phosphate adsorption. Acidic surfaces, enriched in oxygen-containing groups such as carboxyl (–COOH), carbonyl (–C=O), and phenolic hydroxyl (–OH), impart negative surface charge and can enhance adsorption through hydrogen bonding or electrostatic interactions with phosphate species. Conversely, basic surfaces with lower oxygen content and higher π-electron density act as Lewis basic sites, which can become protonated under acidic conditions ($pH < pHpzc$), generating positively charged surfaces that attract negatively charged phosphate ions. The point of zero charge (pHpzc) is a critical parameter, indicating the pH at which the net surface charge is zero. Hai *et al*., [30] suggested that activated carbon using biomass waste with low oxygen content is recommended as it would assist in enhancing AC surface characteristics. Nevertheless, an increase in surface functional groups, such as carboxyl and hydroxyl, correspond to higher volatile matter content, thus improving AC's surface properties [57,58]

Liu *et al.*, [59] reported that nanoscale zero-valent iron–modified biochar had a pHpzc of approximately 7.8, where phosphate adsorption was minimal at low pH due to the predominance of neutral $H_3PO_4$/$H_3PO_3$ species, optimal at pH 7–9, and decreased at pH > 9 as electrostatic repulsion increased. Surface modification can shift the pHpzc and functional group distribution, thereby tuning electrostatic interactions to enhance adsorption under target conditions.

Precursor composition also plays a key role as biomass with low oxygen content favours dense carbon structures with enhanced surface characteristics, while higher volatile matter correlates with greater formation of surface functional groups such as carboxyl and hydroxyl, which improve adsorption capacity [31,53,54] . In aqueous systems, the presence of dissolved salts can further influence phosphate adsorption. Monovalent salts (e.g., NaCl, KCl) increase ionic strength, which can screen electrostatic interactions and reduce adsorption efficiency, while competing anions ($Cl^-$, $NO_3^-$, $SO_4^{2-}$) may occupy adsorption sites. In contrast, multivalent cations (e.g., $Ca^{2+}$, $Mg^{2+}$, $Fe^{3+}$) can act as bridging ions between negatively charged phosphate species and the carbon surface, promoting electrostatic neutralization or complex formation, thereby enhancing adsorption. Consequently, the interplay of surface functional groups, electrostatic environment, precursor composition, and solution chemistry collectively governs the phosphate adsorption performance of activated carbon and biochar.

### *3.4 Activation Method*

There are two activation pathways to synthesize activated carbon which are physical and chemical activation. Physical activation typically uses high temperatures (700 to 900°C) using conventional furnace heating or microwave radiation, which can yield high surface areas [32]. Under the same pyrolysis conditions, different biomass feedstocks will yield biochar with varying physicochemical properties [60].

The microwave radiation involves the use of microwave radiation to heat the precursor material, which is carbon rich material for the production of activated carbon. Firstly, the precursor is carbonized through a heating process to form a carbonaceous structure. Then, the carbonized material is being exposed to microwave radiation, which rapidly heats and activates the carbon structure. There are several advantages using microwave radiation such as high efficiency, time saving, using electrical energy instead of heat energy, lower temperature involved, low-cost equipment and safer compared to conventional furnace heating processing [32]. The microwave activation process leads to the development of a porous network with high surface area and adsorption capacity in a shorter time compared to conventional heating methods. Meanwhile, the conventional furnace heating involves heating the precursor in the absence of oxygen to convert it into a carbonized form. The carbonization process typically takes place at high temperatures (500°C to 900°C) in a controlled environment [32]. After carbonization, the carbonized material is activated using an activating agent such as steam or carbon dioxide at high temperatures. The activation process creates a porous structure with a high surface area on the carbon material which enhanced its adsorption properties.

The main difference between microwave radiation and conventional pyrolysis is in the way the heat is generated. Conventional furnace heating might take longer time compared to microwave heating in order to reach desired level of activation where this slow thermal process might increases the expense associated during the activation process [32]. Fast heating provided by the microwave technique promotes the development of pores in a shorter amount of time than conventional furnace that saves energy [32]. Activated carbon from bamboo processed by microwave heating would have higher BET surface area of AC (807.54 $m^2/g$) compared to furnace heating 255.77 ($m^2/g$) [61]. However, both methods are effective techniques to produce activated carbon with high surface area, high pore volume and high adsorption capacity.

Meanwhile, chemical activation usually used agents like acid and alkali in order to enhance the surface area and pore structure by creating more functional groups. The chemical activation is often preferred compared to physical activation method for activated carbon development due to its ability to create more surface functionality which may be beneficial for specific applications. Study by Sun *et al.,* [62] suggested that the surface area of combined alkali-acid using sodium hydroxide and nitric acid modified precursor increased by 1.4 to 2.0 folds and the total pore volume increased by 1.2 to 1.8 folds as compared to the single chemical modification method. This is because of alkali treatment provides more pores for adsorption and exposed more positions for the next acid treatment.

## 4. Recent Advances on Adsorption of Phosphorus onto ACs Derived from Biowaste

In response to the influencing factors, recent studies have increasingly explored the development of advanced biomass-derived activated carbons with improved adsorption performance. In practical wastewater treatment systems, the integration of multiple modification strategies is often adopted to enhance adsorption efficiency and material functionality. Various physicochemical approaches have been reported for tailoring the structural and surface properties of biomass-derived activated carbon, including hydrothermal carbonization followed by activation, molten salt processing, ball-milling for particle size reduction and surface activation, ultrasound-assisted wet chemical oxidation, and chemical refluxing processes [30]. Although these methods effectively enhance surface area, pore structure, and surface reactivity, most studies focus on general adsorption improvement rather than the selective removal of phosphorus species.

Magnetic modification represents another emerging strategy, where biomass precursors are treated with metal-based reagents to facilitate the deposition of magnetic ions or nanoparticles on the carbon surface and within pore networks, enabling rapid post-treatment separation using an external magnetic field [24].

Beyond material modification, advances in reactor configurations, such as fixed-bed and fluidized-bed systems [30], have been employed to improve thermal degradation efficiency during pyrolysis, leading to activated carbons with enhanced structural properties. However, the synergistic integration of advanced synthesis routes, reactor design, and phosphorus-targeted surface functionality has not been systematically investigated.

## 5. Conclusion and Recommendations for Future Study

While recent studies focusing on biomass-derived activated carbon has shown promise for adsorbing pollutants due to its high surface area and functional groups, there is limited research on its efficiency specifically for phosphorus species (phosphates, orthophosphates, organic P, inorganic P) in domestic wastewater treatment. To the best of recent studies knowledge, the development of biomass-derived activated carbon has low production cost and high availability of the source. However, the efficiency of activated carbon for adsorption performance would varies on each P species, and dependent on several key criteria influencing its ability to capture and remove contaminant. The main factors that would determine a good adsorption performance for activated carbon, are such as surface area, pore structure, surface chemistry, thermal stability, and activation pathways, where the efficacy of diverse P species removal can be studied in future. from biomass for removal of phosphorus-based compounds in domestic wastewater treatment.

## Acknowledgement

The authors acknowledge the financial support from the Ministry of Higher Education (MOHE) under the Fundamental Research Grant Scheme (FRGS) (FRGS/1/2024/TK05/UTM/02/9) and Universiti Teknologi Malaysia for funding under Universiti Teknologi Malaysia Encouragement Grant (Q.J130000.3846.31J75).

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