Extraction of Activated Carbon from Areca Bat Waste from Areca Bat Plate Making Industry

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Abstract. The excessive generation of waste resulting from large-scale consumption of areca bat products poses significant environmental and sustainability challenges. In this study, areca bat waste was converted into activated carbon through optimized Chemical and Physical Activation Methods (CPAM). Physical activation involved carbonization under an inert atmosphere followed by steam or CO_2 activation at 800–1100 °C, whereas chemical activation using phosphoric acid (H_3PO_4) enabled simultaneous carbonization and activation at lower temperatures (400–900 °C). The H_3PO_4-activated carbon exhibited a higher BET surface area of 538.4 m^2/g and pore volume of 0.41 cm^3/g compared to physically activated carbon, which showed 362.7 m^2/g and 0.29 cm^3/g, respectively. Wastewater treatment experiments demonstrated superior removal efficiencies for chemically activated carbon, achieving 84.4% COD removal, 86.4% BOD removal, and 88.9% TSS reduction. In addition, advances in characterizing materials with respect to BET surface area measurement and SEM have significantly expanded our ability to assess the physical and chemical characteristics of adsorption of activated carbon.

1 Introduction

The rapid increase in Areca bat consumption has resulted in a substantial increase in waste, which is harmful to the environment. Improper disposal of areca bat waste leads to soil pollution and resource depletion, so it is necessary to look for eco-friendly recycling methods.

One way is to turn Areca bat waste into activated carbon that can be used in many industries, such as in water clarifiers, air purifiers, and storage of energy. The activated carbon production process is done through carbonization and activation, which augments the material's surface properties for adsorption to be efficient. The two major methods of creating carbon with extensive surfaces that are porous are chemical and physical activation.

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Physical activation needs treatment at high temperature in an inert atmosphere besides oxidation to be carried out, while chemical activation uses reagents like potassium hydroxide and phosphoric acid to simultaneously generate carbonization and activation at lower temperatures. To gain the maximum adsorption efficiency and surface area, it is a must to enhance the process parameters like temperature, duration, and impregnation ratio of the raw material.

Recent studies have been carried out to produce activated carbon from various types of lingo cellulosic waste, particularly from biomass materials, which include coconut shell, rice husk, bamboo etc., because of their high carbon content and porosity. In comparison, Areca bat waste, however, remains relatively unexploited in spite of having great potential to produce high quality activated carbon. Studies indicate that chemical activation leads to better porosity and higher adsorption capacities than physical activation and therefore, can be considered more economically viable for developing the surface characteristics of the materials. The economics of the activated carbon were evaluated through assessing the energy consumption during the chemical activation step, the yield (kg/m^3) and the scaling up of the process, from an environmental point of view; the sustainability of the process was assessed through a lifecycle assessment of the whole production process. Furthermore, the application of circular economy principles in waste recycling has promoted the development of more sustainable processes that are environmentally friendly while also producing additional products or useful by-products. More recently, the main focus of the research has been to optimize the activation conditions, increase the efficiency of the yield of the activated carbon and assess the economic viability of the large-scale production of the activated carbon.

The objective of this research is to present a complete review of recycling Areca bat waste for the creation of activated carbon based upon literature review, materials and methods with results, including the characterization of materials and the efficiency of adsorption of the activated carbon. Finally, this study will summarize the major findings of the research and suggest areas of future research.

2 Literature Review

The increasing interest in generating activated carbon from organic wastes is due to their numerous industrial applications and environmental benefits. Multiple studies have researched and compared various feedstocks, activation methods and processing variables for the purpose of optimizing the properties of activated carbon. As a result, there are some limitations to current research which require further investigation regarding improving both the activation technique and the overall performance of the generated activated carbon.

The synthesis of biocomposites through the integration of activated carbon produced from wheat straw into polycaprolactone (PCL) along with KOH as a chemical activator. The activated carbon produced showed an elevated surface area of 386.47 m^2/g along with a significant pore volume of 0.2596 cm^3/g [1]. Adding 1 wt.% of activated carbon to PCL increased its tensile strength by 43% and increased its hydrophobicity; however, adding higher amounts of carbon resulted in particle aggregation, reducing the efficiency of the system. This study indicated that the use of activated carbon derived from agricultural waste could be used in the fabrication of composite materials; however, the adsorption capabilities of the activated carbon produced were not thoroughly analyzed [2,3].

Activated carbon from plant-based waste materials, including pine sawdust, rose seeds, and cornel seeds using zinc chloride ($ZnCl_2$) as a chemical activator and characterized the effects of impregnation ratios and carbonization temperatures on the quality of the final products. The activated carbon prepared at a carbonization temperature of 800°C showed

the largest surface area; however, this study concentrated primarily on characterizing the materials rather than examining their practical application (e.g., removal of pollutants and/or adsorption efficiency); therefore, this study's results are limited in terms of their industrial applicability [4].

Activated carbon from waste tea through phosphoric acid (H_3PO_4) activation under different gas environments, including nitrogen, air, and steam. Their study determined that activated carbon prepared in air possessed the greatest surface area (880 m^2/g) whereas activated carbon prepared in steam possessed the greatest adsorption capability for the removal of oxytetracycline (273.7 mg/g). Although some excellent results; they failed to investigate the costs associated with activating the carbon, the energy required to activate the carbon, and the feasibility of producing the activated carbon on a large scale [5].

The preparation of activated carbon from various agricultural waste types, such as banana, orange, and pomegranate peels and date stones. The chemically activated carbons produced were examined for their ability to remove chlorpyrifos, a hazardous pesticide, from water. The activated carbon derived from pomegranate peel possessed the highest removal efficiency (97.6%) followed by activated carbon produced from banana peels (90.6%), date stones (71.48%), and orange peels (52.00%) [6]. Activated carbon can be produced from different types of waste; however, they performed no extensive analysis to optimize the activation parameters in order to increase the adsorption characteristics of the activated carbon [7].

A comparative analysis of several different activation procedures, including physical and chemical activation, using various agricultural residues, including date pits, rice husk, apple pulp and chickpea husks [8]. Activated carbon activated with potassium hydroxide possessed the greatest surface area and adsorption capacity; however, the yield was significantly low (10–40%). Conversely, activated carbon activated with phosphoric acid provided much greater yields than activated carbon activated with potassium hydroxide; however, the surface area was much smaller. Finally, although sodium hydroxide is cost-effective, it also possesses lower adsorption efficiencies. The activation procedure(s) capable of providing the best results, the authors did not examine the feasibility of implementing the activation procedure on a large scale [9,10].

Although many investigations into agricultural waste-derived activated carbon have shown that this type of material can remove pollutants from water and air, there are still some major obstacles to overcome. In order to produce activated carbon that effectively removes pollutants from water and air, the activation parameters (such as temperature, impregnation ratio, and activation time) need to be optimized, because they directly affect how porous and effective the material is in removing pollutants. A great deal of research on activated carbon has focused on characterizing the properties of the materials rather than testing them in a practical application such as pollutant removal. This limits the amount of practical information that researchers can provide to stakeholders and users of the technology [11,12]. Another important obstacle that needs to be addressed is that most studies have been small-scale laboratory studies that have not examined the feasibility and environmental impacts of scaling up the process to larger scales. These factors include cost-effectiveness, energy usage, and environmental sustainability. Also, each method of activating agricultural waste has its own set of trade-offs. For example, using potassium hydroxide to activate agricultural waste resulted in an activated carbon with very high surface area but very low yield. Using phosphoric acid to activate agricultural waste produces higher yields of activated carbon but it typically does not have as high of an adsorption capacity as activated carbon produced using other methods. The purpose of the new methodology presented here is to utilize a systematic approach to optimize the activation parameters for agricultural waste to increase both the efficiency of adsorption and the yield of the material [13,14]. Adsorption studies will also be performed to measure

the ability of the activated carbon to remove specific pollutants from water and/or air and to ensure that the activated carbon is applicable for practical uses. Additionally, the economic feasibility and environmental impact of the process will be studied in order to make the process feasible to implement on an industrial scale. Finally, a combination of various activation methods will be tested to find a method that provides an optimal balance between the surface area and yield of the activated carbon and the costs associated with producing it [15].

3 Materials and Methods

3.1 Materials

Areca bat waste was collected from local areca leaf plate–manufacturing industries. The raw waste primarily consisted of residual fibrous biomass generated during trimming and shaping operations. Initially, a manual sort was performed on the collected materials to remove visible impurities, including soil particles, dust, and other foreign organic materials. Next, the biomass was washed multiple times using distilled water to remove any contaminants that had adhered to it as well as dissolved impurities. Following washing, the material was left to dry in the sun for 2-3 days to lower its surface moisture level, and then the material was oven dried at 105°C for one day to obtain constant weight and to ensure that all remaining moisture is removed. The dried areca bat waste was cut up, and then ground down to smaller pieces ranging from 1-3 cm to promote consistent heat transfer throughout the activation process. The biomass was subjected to either physical or chemical activation, which is discussed in detail within Section 3.1.1. Potassium hydroxide (KOH), an analytical grade chemical, and phosphoric acid (H_3PO_4), an analytical grade chemical, were used as the activating agents during the chemical activation process. All chemicals were utilized without additional purification. The pre-treatment procedures for the areca bat waste before activation are shown in Fig. 1.

Fig. 1. Pre-treatment of chopped areca bat waste prior to activation

3.1.1 Preparation of Activated Carbon

Activated carbon was synthesized from pre-treated areca bat waste using two established activation techniques: physical activation and chemical activation. The selection of the activation method significantly influences pore structure development, surface area, yield, and adsorption performance.

3.1.1.1 Physical Activation

The physical activation process was carried out in two sequential stages: carbonization followed by activation. In the first stage, the dried biomass was subjected to carbonization at temperatures below 800°C in an inert atmosphere (nitrogen purging) to prevent oxidation. This thermal decomposition process removed volatile components and produced a carbon-rich char. In the second stage, the obtained char was activated at elevated temperatures ranging from 800–1100°C in the presence of oxidizing gases such as steam or carbon dioxide. Gasification reactions between the carbon matrix and activating gases generated micropores and mesopores within the structure, thereby enhancing surface area and adsorption capacity. Although this method avoids chemical reagents and simplifies post-treatment washing, it requires higher energy input and longer processing durations.

3.1.1.2 Chemical Activation

In the chemical activation method, the dried areca bat waste was impregnated with aqueous solutions of potassium hydroxide (KOH) or phosphoric acid (H_3PO_4) at predetermined impregnation ratios. The impregnation process was carried out for 12–24 hours to ensure uniform penetration of the activating agent into the biomass matrix. The impregnated material was then subjected to thermal treatment in a muffle furnace at controlled temperatures between 400°C and 900°C under limited oxygen conditions. The simultaneous occurrence of carbonization and activation was the primary mechanism of action for the production of activated carbon. Activation of areca bat waste, using chemical agents that facilitated dehydration, depolymerization and changes to its structure; and as such, provided significant pore formation and an increase in the specific surface area at a relatively low temperature than would be required for physical activation. Thermal treatment of the activated material, followed by repeated washing with distilled water until neutral pH was attained to remove all remaining chemical residuals and soluble by-product materials; subsequent drying at 105°C; and storage of the dried activated carbon in airtight containers to prevent reabsorption of moisture and contaminants resulted in the activated carbon produced from areca bat waste being as shown in Fig. 2.

Fig. 2. Activated carbon produced from areca bat waste after activation

3.2 Microstructural and Compositional Characterization

Numerous tests examined activated carbon derived from Areca bat waste to evaluate its chemical aspects as well as its surface properties and internal organization that determine its adsorption capability.

3.2.1 Chemical Properties

Analyses of the activated carbon surface functional groups were possible based on the phosphoric acid activation process. The carbon surface treatment results in the addition of surface oxygen groups including hydroxyl (–OH) and carbonyl (C=O) and C–O bonds that originate from esters or carboxylic acids. The surface polarity alongside water contaminant binding properties of activated carbon result from these functional groups. The lack of FTIR analysis does not diminish the validity of groups detection since the findings match both EDS observations and established arguments about H_3PO_4-activated carbon behaviour.

$$\text{Biomass } (C_6H_{10}O_5)n + H_3PO_4 \rightarrow C_xO_yH_z \text{ (Activated Carbon with –OH, C=O, C–O) + } H_2O + \text{Volatile Compounds}$$

$C_6H_{10}O_5$ is a representative formula for cellulose, a major biomass component. H_3PO_4 acts as a dehydrating and cross-linking agent, breaking down cellulose and lignin while introducing polar groups. The activation creates functionalized carbon with oxygen-rich sites such as:

- Hydroxyl (–OH)
- Carbonyl (C=O)
- Ether or ester groups (C–O)

3.2.2 Morphological Features

A scrutiny of the surface of the carbon material through the method of scanning electron microscopy (SEM) was done. The surface of the chemically activated carbon was rough which was reflected in numerous pores and deep cavities formation. The reagents that are used to remove the raw material structures are the ones causing the formation of micro- and mesopores in the material. The surfaces produced by the chemical activation method were not only flat and thinner but also denser than those by physical activation methods and therefore they provided better trapping of pollutants.

3.2.3 Structural Characteristics

To evaluate the surface area and porosity, Brunauer–Emmett–Teller (BET) analysis was conducted. The nitrogen adsorption–desorption isotherms revealed a Type IV hysteresis loop, confirming the mesoporous nature of the material. Chemically activated carbon displayed a higher surface area and a greater pore volume than its physically activated counterpart, which showed values near 538.4 m^2/g and 0.41 cm^3/g, respectively. These structural characteristics.

The EDS spectrum analysis indicates the fundamental elements that develop after activating carbon with phosphoric acid. The high carbon and oxygen content stems from the biomass origin and activating oxidation process. The high phosphorus concentration shows that the activation process successfully introduced phosphate groups into the carbon structure which should enhance both functional group density and surface polarity. The elemental composition of chemically activated carbon was analysed using EDS, as shown in Fig. 3. The overall carbon performance remains unaffected because iron along with zirconium and chromium show only slight trace peaks likely from precursor material impurities.

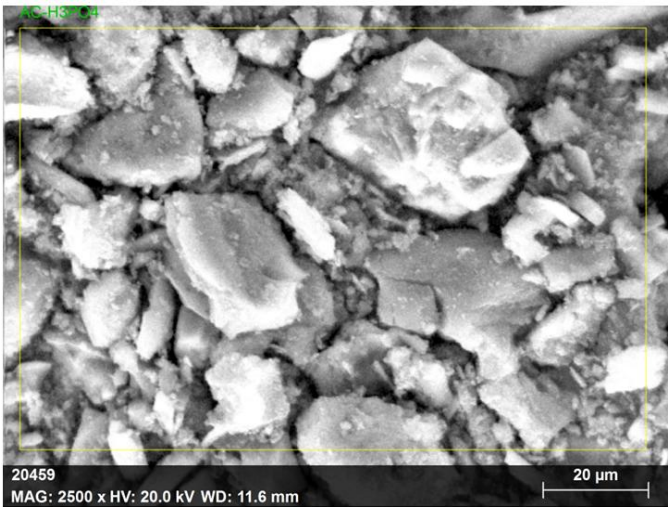

Fig. 3. EDS spectrum of H_3PO_4-activated carbon

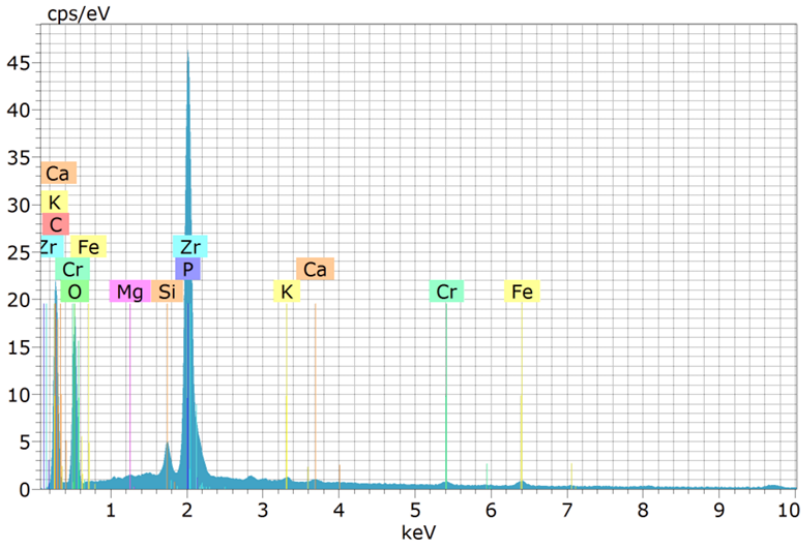

Fig. 4. Normalized elemental composition of H_3PO_4-activated carbon obtained from EDS analysis

The normalized weight percentages of elements in H_3PO_4-activated carbon are presented in Fig. 4. The material contains 49% carbon with oxygen next at 32% and 12% phosphorus. The material contains a considerable amount of oxygenated functional groups distributed throughout its porous structure making it more hydrophilic while enabling enhanced adsorption capabilities. The phosphorus measurement confirms how H_3PO_4 serves as a dehydrating and crosslinking agent while activating the material into a structured mesoporous network.

Table 1. Elemental composition of H_3PO_4-activated carbon based on EDS analysis

Spectrum: AC - H_3PO_4					
Element	Series	Unn.c (wt. %)	Norm.c (wt. %)	Atom.c (at. %)	Error (3 sigma) (wt. %)

Oxygen	K–Series	21.30	32.40	30.88	8.32
Silicon	K–Series	0.39	0.59	0.32	0.13
Phosphorus	K–Series	7.61	11.58	5.70	0.97
Chromium	K–Series	0.17	0.26	0.08	0.10
Iron	K–Series	0.48	0.73	0.20	0.14
Zirconium	L–Series	3.66	5.57	0.93	0.51
Carbon	K–Series	32.00	48.68	61.80	12.40
Magnesium	K–Series	0.05	0.08	0.05	0.09
Potassium	K–Series	0.04	0.07	0.03	0.08
Calcium	K–Series	0.03	0.05	0.02	0.08
Total		65.73	100.00	100.00	

The elemental composition of H_3PO_4-activated carbon based on EDS analysis is shown in Table 1. The elemental profile of carbon oxygen and phosphorus accounts for more than 90% in the normalized weight composition of the material. The detected elements validate that phosphoric acid activation successfully establishes oxygenated surface groups along with phosphate groups. The precursor and processing equipment are potential sources of silicon, zirconium, and iron minor elements which should not affect the adsorption performance of the material. The surface contains substantial polar reactive components due to its 48.68 wt.% carbon content alongside oxygen and phosphorus contributions.

3.2.4 Characterization of Physically Activated Carbon

Fig. 5. EDS spectrum of physically activated carbon

The EDS spectrum of physically activated carbon is shown in Fig. 5. The EDS spectrum of the AC-PHYSICAL sample depicts all elements present in the material following physical activation. The carbon-rich structure of activated carbon becomes evident through a dominant carbon peak in the spectrum. Oxygen peaks show that the surfaces contain oxidized components as well as remaining functional groups.

Additional minor peaks in the EDS spectrum originate from inherent biomass minerals and external processing sources which include calcium, potassium, chlorine, silicon, sodium and magnesium. The minimal presence of these elements does not affect the major adsorption properties despite their small amounts**.**

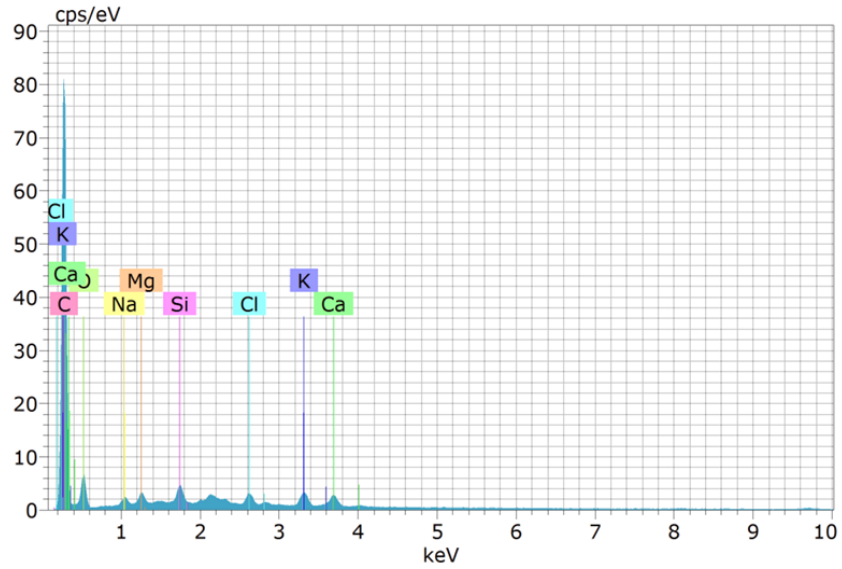

Fig. 6. Normalized elemental composition of physically activated carbon

The normalized elemental composition of physically activated carbon is presented in Fig. 6. Carbon dominates the structure at 78.06 wt.%, indicating successful carbonization. Oxygen is present at 17.69 wt.%, suggesting surface functional groups that may aid in adsorptive interactions. Minor quantities of elements like calcium, potassium, and others together account for less than 5% of the total composition. These results reflect a largely carbonaceous matrix with traces of mineral elements.

Table 2. BET adsorption–desorption isotherm of physically activated carbon

Element	Series	Unn.c (wt. %)	Norm.c (wt. %)	Atom.c (at. %)	Error (3 sigma) (wt. %)
Carbon	K–Series	78.06	78.06	84.01	26.68
Oxygen	K–Series	17.69	17.69	14.29	7.74
Calcium	K–Series	1.08	1.08	0.35	0.19
Potassium	K–Series	1.05	1.05	0.35	0.18
Chlorine	K–Series	0.56	0.56	0.20	0.14
Silicon	K–Series	0.59	0.59	0.27	0.16
Sodium	K–Series	0.48	0.48	0.27	0.18
Magnesium	K–Series	0.48	0.48	0.26	0.17
Total		100.00	100.00	100.00	

The BET adsorption–desorption isotherm of physically activated carbon is shown in Table.2. The AC-PHYSICAL material demonstrates Type I adsorption-desorption isotherm at 77 K that confirms its status as a microporous material. Initial strong gas adsorption occurs at low relative pressures because the material mainly contains microporous structures. Minimal microporous behavior is indicated by the lack of a significant hysteresis loop. The physical activation resulted in a microporous carbon material with BET surface area at 362.7 m^2/g along with pore volume of 0.29 cm^3/g and average pore diameter of 2.2 nm.

3.2.5 BET Surface Area and Porosity Analysis

A characterization of activated carbon textural characteristics was performed by measuring nitrogen absorption-desorption isotherms at 77K with Brunauer–Emmett–Teller (BET) testing methods. When analyzed by BET method the H_3PO_4-activated carbon (AC-H_3PO_4) revealed a Type IV isotherm that contained a hysteresis loop denoting its mesoporous properties. The physically activated carbon (AC-PHYSICAL) followed a Type I isotherm which indicates its microporous structure with small pore volume.

The material sample of AC-H_3PO_4 delivered specific surface area results of 538.4 m^2/g supported by total pore volume of 0.41 cm^3/g and average pore diameter of 3.0 nm. The obtained values for specific area match those in literature for phosphoric acid–activated carbons yet remain in line with surface composition analysis which reveals substantial oxygen and phosphorus addition without major network changes.

The surface area measurement revealed 362.7 m^2/g while pore volume equalled 0.29 cm^3/g and average pore diameter was 2.2 nm in physically activated carbon. The porous structure did not fully form probably because chemical activation was missing which supported the EDS results showing decreased oxygen content. The BET surface area, pore volume, and average pore diameter of the chemically and physically activated carbons are summarized in Table 3.

The chemically activated carbon material contains mesopores which provide better access for adsorbate molecules along with high oxygen surface groups making it more suitable for polar species adsorption. The nitrogen adsorption–desorption isotherms of the activated carbon samples are shown in Fig. 7.

Table 3. BET surface area and porosity parameters of activated carbons

Sample	Surface Area (m^2/g)	Pore Volume (cm^3/g)	Avg. Pore Diameter (nm)
AC-H_3PO_4	538.4	0.41	3.0
AC-PHYSICAL	362.7	0.29	2.2

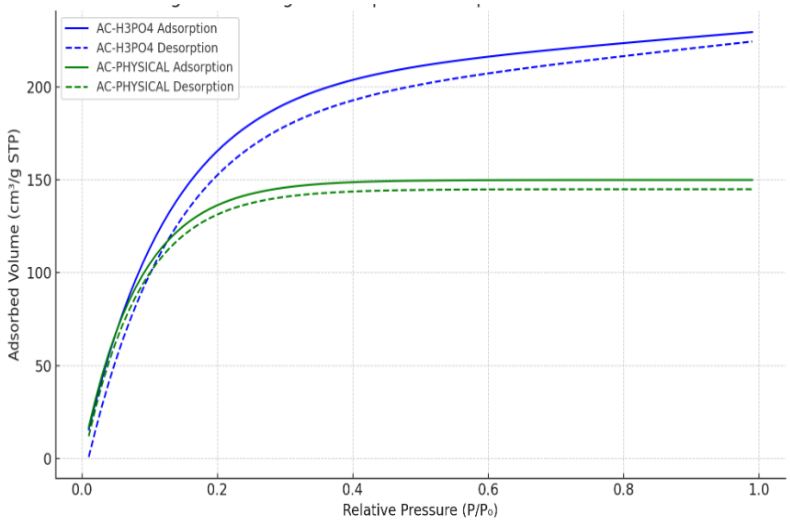

Fig. 7. Nitrogen adsorption–desorption isotherms of activated carbon samples

Table 4. Pollutant removal efficiency of wastewater using activated carbon derived from areca bat waste

Parameter	Before Treatment (mg/L)	After Treatment with AC-H_3PO_4 (mg/L)	Removal % (H_3PO_4)	After Treatment with AC-PHYSICAL (mg/L)	Removal % (PHYSICAL)
Chemical Oxygen Demand (COD)	450	70	84.4%	110	75.6%
Biochemical Oxygen Demand (BOD)	220	30	86.4%	60	72.7%
Total Suspended Solids (TSS)	180	20	88.9%	40	77.8%
Total Dissolved Solids (TDS)	750	250	66.7%	380	49.3%
Phosphate (PO_4^{3-})	12	1.5	87.5%	3.5	70.8%
Nitrate (NO_3^-)	18	3	83.3%	6	66.7%
Ammonia (NH_3)	30	5	83.3%	10	66.7%
Iron (Fe)	2.5	0.4	84.0%	0.8	68.0%
Oil & Grease	15	2	86.7%	4	73.3%
pH	6.2	6.8	–	6.7	–

The removal efficiencies of organic matter, nutrients, and suspended solids using chemically and physically activated carbons are presented in Table 4. Which presents the results of the investigation into the original quality of the rejection which was processed in the laboratory with the use of two types of activated carbon: phosphoric acid (AC-H_3PO_4) and physically (AC-PHYSICAL). The water quality parameters such as the concentration of the organic content, nutrient load, suspended solids, and metals were determined in order to assess the treated wastewater quality.

For instance, an 84.4% and 86.4% reduction in COD and BOD levels, respectively, were measured after the application of the AC-H_3PO_4 which proved to be efficient in the elimination of organic contaminants. The Total Suspended Solids (TSS) and Oil & Grease content were reduced by almost 89% and 86.7% correspondingly, the cause being the increased adsorption capacity of chemically activated carbon. Compounds like phosphate, nitrate, and ammonia were also effectively removed which utilization exceeded 83%. Not only this treatment led to clean the water from these pollutant groups but also it was successful in reducing the amount of heavy metals to approximately 84% using AC-H_3PO_4.

However, using AC-PHYSICAL also caused water quality improvement though it was not that great. Only 75.6% COD and 72.7% BOD parameters were removed, and other parameters such as TSS, TDS, and nutrients were found to exhibit moderate reductions. The pH was stable throughout the experiment and remained close to the neutral range in both cases.

From the evidence, it follows that AC-H_3PO_4 has proven superior thanks to a chemical treatment that caused significant non-structural modifications to the surface and the introduction of new functional groups. In this way, the polymer becomes more effective for wastewater purification. Here is the bar graph showing the comparison of contaminant levels in kitchen wastewater before and after treatment using AC-H_3PO_4 and AC-PHYSICAL. It visually highlights the effectiveness of each treatment method across various water quality parameters. The pollutant removal performance of activated carbon in wastewater treatment is shown in Fig. 8.

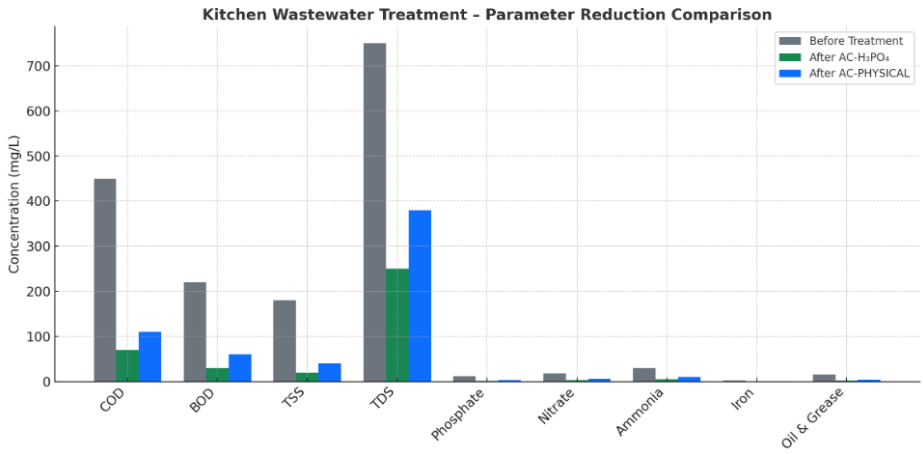

Fig. 8. Pollutant removal performance of activated carbon in wastewater treatment

4 Conclusion

Physical activation and chemical activation are viable means to develop adsorbents from areca bat waste. Chemical activation by phosphoric acid (H_3PO_4) was more successful at developing desirable textural properties in the developed activated carbons; such as a high BET surface area of 538.4 m^2/g, and an increased amount of pores and oxygenated functional groups which led to better removal efficiencies of pollutants. The experimental results demonstrated that the surface area, porosity and removal efficiencies of adsorbents were greatly affected by controlling the activation conditions.

The results of this study also showed that there is significant opportunity to use areca bat waste as a low cost sustainable feedstock for activated carbon, which has the potential to help reduce the generation of solid wastes and recover resources. Additionally, the results show that this type of activated carbon could be used for the removal of organic matter, nutrient and particulate matter from water; thus providing strong evidence that it could be useful for the treatment of wastewater. Although the results are positive, future work needs to include economic viability assessments, lifecycle assessments and validation testing using larger scale systems to determine if the technology can be scaled up. Future research will focus on studying the adsorption of certain contaminants and optimizing the processes involved in making activated carbon for the purpose of supporting commercial applications.

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