

Optimizing Ammonia Removal in Recirculating Aquaculture Systems Using NaOH-Activated Sugarcane Bagasse Carbon

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ABSTRACT

This study evaluates the effectiveness of activated carbon produced from sugarcane bagasse as an ammonium filter in a Recirculating Aquaculture System (RAS) for Nile tilapia (*Oreochromis niloticus*). The research involved five different treatments with varying amounts of carbon mass. The results indicated that the highest carbon mass treatment (P5) achieved superior water quality and fish growth performance, including a specific growth rate (SGR) of 3.345% per day, the lowest feed conversion ratio (FCR) of 0.829, and a 100% survival rate. Fourier Transform Infrared (FTIR) and Scanning Electron Microscope (SEM) analyses confirmed significant pore enlargement and the presence of functional groups facilitating ammonium adsorption. The findings demonstrate the potential of sugarcane bagasse-derived activated carbon as a sustainable and cost-effective solution for improving water quality and promoting fish growth in aquaculture systems.

Keywords: Activated carbon; Ammonium adsorption; Nile tilapia growth; Recirculating Aquaculture Systems (RAS); Sugarcane bagasse

1. Introduction

Tilapia (*Oreochromis niloticus*) is a key freshwater aquaculture species in Indonesia due to its rapid growth, resilience, and economic value. In 2021, national tilapia production reached 1.35 million tons, a 9.63% increase from 2020, with further expansion targeted at 2 million tons by 2023 [1]. Aceh has experienced a notable annual production growth of 29.39% from 2017 to 2022. While this increase benefits the economy, it also raises environmental concerns, particularly regarding waste accumulation. Intensive tilapia farming generates large amounts of uneaten feed, feces, and metabolic waste, contributing to high levels of pollutants such as phosphorus (PO_4^{3-}), nitrates (NO_3^-), nitrites (NO_2^-), and ammonia ($\text{NH}_3/\text{NH}_4^+$) [2]. Ammonia is particularly harmful, as excessive concentrations can cause fish stress, hinder growth, and lead to higher mortality rates [3]. Poor waste management can also degrade water quality and disrupt aquatic ecosystems, posing sustainability challenges for aquaculture operations. Therefore, maintaining water quality is crucial for sustaining tilapia production. Effective ammonia removal is necessary to ensure optimal conditions in fish farms. One promising approach to addressing this challenge is implementing advanced water treatment technologies, such as Recirculating Aquaculture Systems (RAS), which efficiently manage water quality while minimizing environmental impact.

Recirculating Aquaculture Systems (RAS) have emerged as an advanced solution for improving water quality and optimizing resource use in fish farming. These systems continuously recycle water, reducing dependency on frequent water exchanges and mitigating pollution risks. RAS employs multiple filtration processes,

including sterilization, chemical, biological, and mechanical filtration, to remove excess nutrients and contaminants [4, 5]. Among the filtration components, activated carbon is widely used for its high adsorption capacity, effectively reducing ammonia, nitrate, and nitrite levels [6]. With its large surface area and porous structure, activated carbon efficiently removes organic and inorganic pollutants, improving water quality and fish health. Additionally, activated carbon can be synthesized from agricultural waste, making it a cost-effective and sustainable filtration option. Various organic materials, including corn cobs, coconut shells, banana stems, and sugarcane bagasse, have been explored as sources for activated carbon production [7, 8]. Sugarcane bagasse, in particular, is abundant and rich in carbon content, making it a promising precursor. The activation process, often using NaOH treatment, enhances its adsorption properties. Research has demonstrated that NaOH-activated sugarcane bagasse carbon effectively reduces ammonia levels in RAS, supporting sustainable aquaculture practices. Optimizing this filtration approach can significantly improve water management in intensive fish farming systems.

In Banda Aceh, waste production increases significantly during Ramadan, reaching 289 tons per day, primarily due to food vendors selling iftar meals. Among the major waste materials generated is sugarcane bagasse, as sugarcane juice is a popular beverage throughout the year. Vendors operating in various locations, such as Lampineung and Ulee Lheue, produce substantial amounts of bagasse, with each vendor generating approximately 60 kg daily. While some of this waste is repurposed as animal feed, a considerable portion is discarded. Sugarcane bagasse is rich in or-

ganic components, containing 40–50% cellulose and 25–35% hemicellulose, making it a valuable raw material for various applications [7]. Its high carbon content presents an opportunity for sustainable waste utilization, particularly in the production of activated carbon. Activated carbon derived from sugarcane bagasse has been widely explored for its adsorption properties in environmental applications. This study investigates the potential of NaOH-activated sugarcane bagasse carbon as an effective water filtration medium in Recirculating Aquaculture Systems (RAS) for tilapia farming. By utilizing this abundant agricultural waste, the research aims to enhance water quality management in intensive aquaculture while promoting a sustainable and cost-effective approach to waste recycling.

2. Materials and Methods

2.1 Type and research plan

This study is quantitative in nature and was conducted from May to December 2024 at the Fish Breeding and Reproduction Laboratory, Faculty of Marine and Fisheries, Syiah Kuala University. The materials used include sugarcane bagasse waste, collected from sugarcane juice vendors in Kuta Alam, Banda Aceh, Aceh Province, Indonesia (5°33'45.0"N 95°20'36.5"E), along with $C_6H_5Na_3O_7$, NaClO, C_6H_5OH , $C_5FeN_6Na_2O$ (0.5%), distilled water, filter paper, and aquaculture water samples. The equipment used includes a UV-Visible Spectrophotometer, Fourier Transform Infrared (FTIR) Spectrometer, Scanning Electron Microscope (SEM), X-Ray Diffraction (XRD) system, aerators, pH meters, DO meters, PVC pipes, buckets, and other basic laboratory tools.

This study employs an experimental method using a Completely Randomized Design (CRD) with four treatments

and three replications each. The treatments are based on variations in activated carbon mass per 16 L of aquaculture water, as adapted from previous studies [9]. The treatment groups are as follows:

- P1: Control (no activated carbon)
- P2: 5 g of activated carbon
- P3: 10 g of activated carbon
- P4: 15 g of activated carbon
- P5: 20 g of activated carbon

2.2 Data collection methods

2.2.1 Synthesis and characterization of activated carbon

Sugarcane bagasse was collected from vendors around Banda Aceh. The bagasse was cut into 1-2 cm pieces using scissors and then air-dried under the sun for 4 days, covered with a 90% shade cloth (paranet). The bagasse was then ground, and 300 g of the powder was carbonized for 1 hour at 300°C. The carbonized product was activated by soaking it in 1 M NaOH solution. The activated carbon was washed with distilled water until the pH reached neutral (pH 7), then dried in an oven for 2 hours at 120°C.

2.2.2 Characterization of the prepared activated carbon

The adsorbent's morphological features were analyzed using a scanning electron microscope (SEM), specifically the Hitachi SU3500. Before the examination, the samples were adhered to double-sided carbon conductive tape. The structural characteristics were investigated using X-ray diffraction (XRD) with a D8 Advance instrument equipped with a Cu $K\alpha$ radiation source ($\lambda = 1.540598 \text{ \AA}$), operating at 30 kV and 15 mA. The scanning was performed over a 2θ range of 5° to 80°, with a step

increment of 0.2 seconds per step to ensure high-resolution analysis. Functional group identification and transmittance spectra of the activated carbon were determined via Fourier-transform infrared spectroscopy (FTIR) using a Thermofisher Scientific Nicolet iS50, within the wavenumber range of 500 to 4000 cm^{-1} .

2.2.3 *Tilapia cultivation*

The cultivation setup consisted of 12 maintenance containers, each a 50 cm diameter and 30 cm high basin. For water circulation and filtration, 1/5-inch PVC pipes were used. A total of 120 tilapia fish, measuring 5-7 cm, were used. Water circulation was achieved using a submersible pump. Commercial feed (30% protein) was provided during the cultivation period using the at satiation method. Feeding times were at 08:00, 12:00, and 16:00 WIB, with a feeding rate of 5% of body weight. The cultivation period lasted 28 days.

2.2.4 *Water quality measurement*

The main water quality parameter in this cultivation was NH_3 concentration. The measurements were conducted under specific conditions following the Indonesian National Standard (SNI) to accurately assess the levels using a spectrophotometer. The ammonia (NH_3) concentration was determined by measuring absorbance with a UV-Visible spectrophotometer at a wavelength of 640 nm (SNI 06-6989.30-2005).

2.2.5 *Data processing*

Data processing for water quality measurements, absolute weight and length, feed efficiency, and survival rate was conducted using Microsoft Excel 2019. Statistical analysis was performed using ANOVA (Analysis of Variance) in SPSS version 26 to determine significant differences among treatments. If a significant effect was observed, Duncan's Multiple Range Test

(DMRT) was applied to compare treatment means based on the Coefficient of Variation (CV). The DMRT analysis ensured a detailed evaluation of differences between treatment groups, providing a more precise interpretation of ammonia removal efficiency and fish growth performance [9]. SEM results were analyzed using the ImageJ application. Data tabulation and graphing for FTIR and XRD were carried out using OriginLab 2019. The diffraction pattern references for XRD results were based on the International Centre for Diffraction Data (ICDD).

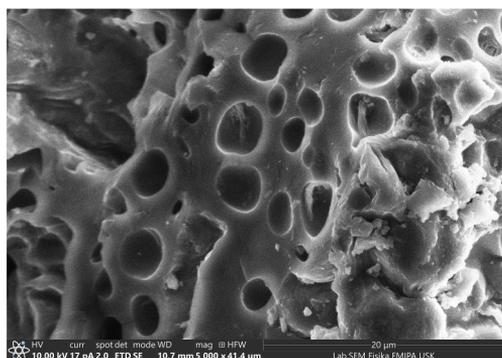
3. Results and Discussion

3.1 Synthesis and characterization of activated carbon

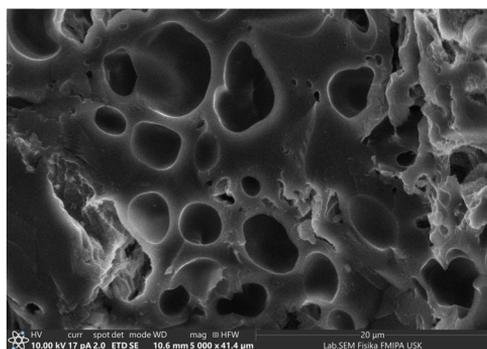
3.1.1 *Scanning Electron Microscope (SEM) Analysis*

The synthesis of activated carbon from sugarcane bagasse involved a two-step process: carbonization followed by chemical activation. Initially, the bagasse was carbonized at 300°C for one hour, a process which removes volatile components and leaves behind a carbon-rich material. This carbonization step is crucial as it lays the foundation for the development of the porous structure necessary for effective adsorption. Activated carbon was characterized using a Scanning Electron Microscope (SEM) to observe the surface of the activated carbon. A magnification of 5000x was chosen to examine the pore structure formed and the surface morphology of the activated carbon. The SEM surface morphology of the activated carbon at each concentration is shown in Fig. 1.

Following carbonization, the carbon material was activated using a 1 M NaOH solution for 24 hours. Chemical activation with NaOH is known to enhance the development of micropores and mesopores



(a)



(b)

Fig. 1. SEM images of activated carbon at 5000x magnification: (a) before activation, (b) after activation.

in the carbon structure, which significantly increases its surface area and adsorption capacity. During the activation process, NaOH acts as a catalyst to etch the carbon surface and create additional porous sites. This step is critical in increasing the number of active sites available for adsorption. Scanning Electron Microscopy (SEM) analysis provided valuable insights into the structural changes that occurred during the activation process. The SEM images revealed a marked increase in pore diameter from $17.5 \pm 2.3 \mu\text{m}$ before activation to $38.5 \pm 2.3 \mu\text{m}$ after activation. In another study, the synthesis of activated carbon from sugarcane bagasse was performed using 1,000 mL of 85% phosphoric acid so-

lution as the activator. The activated carbon produced was tested for its efficacy in mercury adsorption, and it displayed a pore size of $31.562 \mu\text{m}$ [10]. This increase in pore size is indicative of the successful formation of a more developed porous network within the carbon material. The larger pore diameters suggest that the activation process has effectively enlarged the pores, allowing for improved access and adsorption of contaminants. In another study, porous activated carbons derived from waste sugarcane bagasse were prepared using various activating agents, including air, CO_2 , H_3PO_4 , and NaOH. These porous activated carbons were characterized by a pore size predominantly within the range of 2–100 nm, making them suitable for CO_2 adsorption applications [11].

The significant enlargement of pore size can be attributed to the action of NaOH, which not only increases the surface area but also alters the surface chemistry of the carbon. NaOH activates the carbon by creating new pores and widening existing ones, which enhances the material's ability to adsorb various substances [12]. This is particularly important for applications requiring high adsorption capacities, such as in water treatment or air purification. The increase in pore size observed in this study aligns with established theories of chemical activation. NaOH is known to generate a high surface area and porosity in activated carbon by breaking down carbon structures and removing impurities. The expansion of pore sizes allows for better interaction between the carbon surface and adsorbates, which improves the efficiency of the adsorption process [13].

3.1.2 X-ray diffraction (XRD) analysis

The X-ray diffraction (XRD) analysis of synthesized activated carbon, both

before and after activation, reveals significant structural information crucial for understanding its properties and potential applications (Fig. 2(a)). The XRD patterns show prominent peaks in the ranges of 10–20 degrees and 20–30 degrees, commonly associated with the (002) and (100) planes of graphitic carbon, respectively. These peaks suggest the presence of graphitic microcrystallites, indicating that some degree of graphitic order is retained even after activation. This retention is beneficial for applications requiring electrical conductivity and high surface area, such as adsorption and catalysis [14]. The peak at 10–20 degrees, linked to the (002) plane, implies some level of graphitic layer ordering, while the peak at 20–30 degrees, related to the (100) plane, reflects in-plane ordering of carbon atoms, suggesting the carbon retains structural integrity after activation [15].

However, a notable observation is the absence or weak presence of a peak around 40–45 degrees, typically associated with the (101) plane of graphitic carbon. Several factors might contribute to this discrepancy. One possibility is that the activation process, which involved chemical treatment with NaOH, caused partial disruption or disorientation of the graphitic layers. This disruption may result in smaller crystallite sizes or a transition towards a more amorphous structure, thus diminishing the visibility of the (101) peak. Additionally, the carbon may have a significant amount of amorphous content, which does not exhibit sharp diffraction peaks, possibly masking the (101) peak. The increased porosity and defect sites introduced during activation might also contribute to this observation, indicating that the material has undergone structural changes that reduce its crystallinity. The absence of a significant (101) peak might not adversely affect adsorption

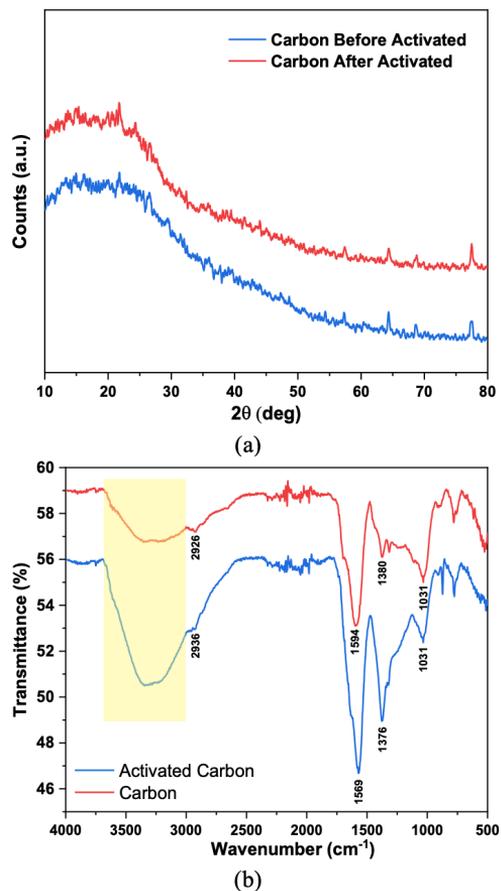


Fig. 2. (a) XRD pattern and (b) FTIR spectrum of sugarcane bagasse activated carbon before and after activation with 1 M NaOH activator.

capacity but may suggest a more complex pore structure advantageous for adsorbing specific molecules [16].

The activation process appears to enhance the amorphous nature of the carbon by introducing a higher number of defects and increasing porosity. This feature could be beneficial for adsorption applications where a higher surface area and more active sites are desired. The porosity introduced during activation increases the material's surface area, potentially enhancing its capacity to adsorb gases and pollutants, which is critical for applications like wa-

ter purification or gas adsorption. Furthermore, for catalytic applications, maintaining some graphitic structure ensures good electrical conductivity, which is crucial for electron transfer processes. Despite the absence of a clear (101) peak, the presence of graphitic characteristics as indicated by the (002) and (100) peaks suggests that the material still possesses some beneficial properties for catalytic applications, including stability and conductivity [14].

The XRD analysis of the synthesized activated carbon shows a complex interplay between graphitic order and amorphous characteristics, influenced significantly by the activation process. The presence of peaks at 10–20 degrees and 20–30 degrees indicates that graphitic ordering is maintained to some extent, while the absence of a peak at 40–45 degrees points to increased amorphous content and possible structural disruption. These structural characteristics highlight the effectiveness of using NaOH as an activating agent to balance porosity and structural integrity, making the activated carbon suitable for various applications, from adsorption to catalysis. Future studies should focus on optimizing activation parameters to fine-tune the balance between amorphous and graphitic structures, depending on the specific application requirements.

3.1.3 Fourier Transform Infrared (FTIR) spectroscopy characterization

The Fourier Transform Infrared Spectroscopy (FTIR) analysis of carbon samples before and after activation provides valuable insights into the structural changes and functional groups present in the material (Fig. 2(b)). The data indicates shifts in the wavenumber regions corresponding to various types of molecular vibrations, which are indicative of the

Table 1. FTIR measurement parameters.

No	Wavenumber Carbon		Type of Vibration
	Before Activation	After Activation	
1	3682-3000	3695-2984	O-H <i>Stretch</i>
2	2926	2936	C-H <i>Stretch</i>
3	1594	1569	C-C <i>Aromatic Ring Stretch</i>
4	1380	1376	C-H <i>Rock</i>
5	1031	1031	C-O <i>stretch (Alcohol)</i>

chemical modifications occurring due to the activation process. This analysis focuses on key vibrations such as O-H stretch, C-H stretch, C-C aromatic ring stretch, C-H rock, and C-O stretch (Table 1).

The O-H stretch is observed in the broad wavenumber range of 3682–3000 cm^{-1} before activation and slightly shifts to 3695–2984 cm^{-1} after activation. This shift suggests a change in the hydrogen bonding environment, which could be attributed to the activation process. The activation likely introduces more hydroxyl groups or alters existing ones, enhancing the material's hydrophilicity [16]. These hydroxyl groups may play a crucial role in adsorption processes, as they can form hydrogen bonds with adsorbates, thereby enhancing the interaction between the carbon surface and the adsorbing molecules. The presence of O-H stretching vibrations indicates that water molecules or hydroxyl functional groups are retained on the surface, which is crucial for interactions with polar adsorbates. The C-H stretch shows a minor shift from 2926 cm^{-1} to 2936 cm^{-1} , indicating a slight alteration in the aliphatic hydrocarbon chains' environment [15]. This shift may be due to the removal of some hydrogen atoms or the creation of more unsaturated carbon sites during the activation. The activation process might involve the removal of volatile

organic compounds or the breakdown of aliphatic side chains, resulting in a higher concentration of aromatic or more stable carbon structures. The presence of C-H stretching indicates that some aliphatic content remains, which could contribute to the hydrophobic properties of the activated carbon, making it suitable for the adsorption of non-polar organic compounds.

A significant observation is the shift in the C-C aromatic ring stretch from 1594 cm^{-1} to 1569 cm^{-1} . This shift suggests that the activation process influences the aromatic structures within the carbon matrix. It could imply either the formation of new aromatic structures or the rearrangement of existing ones, which might result from the dehydrogenation and condensation reactions during activation. The alteration in aromatic ring structures can significantly affect the carbon's adsorptive properties, as aromatic structures are known for their high surface area and ability to interact with aromatic pollutants through $\pi - \pi$ interactions. This feature is advantageous for applications in removing aromatic contaminants from wastewater or air. The C-H rock, which exhibits a minor shift from 1380 cm^{-1} to 1376 cm^{-1} , represents the bending vibrations of C-H bonds in the carbon material [14]. This minor shift indicates that there is some change in the carbon material's structural integrity but not significant enough to suggest complete restructuring. These vibrations are usually associated with the presence of methyl and methylene groups, indicating that the activated carbon retains some aliphatic chains even after activation. These chains can contribute to the adsorption of specific organic compounds, complementing the overall adsorptive capability of the carbon.

Lastly, the C-O stretch associated with alcohol groups remains unchanged at

1031 cm^{-1} before and after activation. This invariance suggests that the alcohol functional groups are not significantly affected by the activation process. The presence of C-O stretching vibrations indicates that alcohol groups remain on the surface, which could contribute to the carbon's overall polarity. These functional groups might provide active sites for adsorbing polar contaminants, enhancing the carbon's versatility in adsorbing a wide range of pollutants, from non-polar to polar substances.

3.2 Indophenol standard curve

The standard curve measurement for evaluating ammonium adsorption was performed using Indophenol on the activated carbon, with absorbance determined at a wavelength of 425 nm (Fig. 3(a)). This specific wavelength is crucial as it corresponds to the optimal absorbance peak for the yellow to brownish color complex formed between Indophenol and ammonium ions, providing maximum sensitivity for the detection process [17]. To establish the calibration curve, ammonium solutions at concentrations of 1, 2, 4, 6, 8, and 10 ppm were prepared. The linear relationship between the absorbance (y) and the ammonium concentration (x) was found to be represented by the equation $y = 3.9984x - 0.0008$ (Fig. 3(b)). The high slope value of 3.9984 indicates a strong response of absorbance to changes in ammonium concentration, making the method highly sensitive. The near-zero intercept (-0.0008) implies minimal baseline interference, suggesting that the method can accurately measure low concentrations of ammonium without significant background noise. Using the calibration curve data and applying the formula $LOD = 3 \times (\sigma)/\text{slope}$, the limit of detection for ammonia is estimated to be approx-

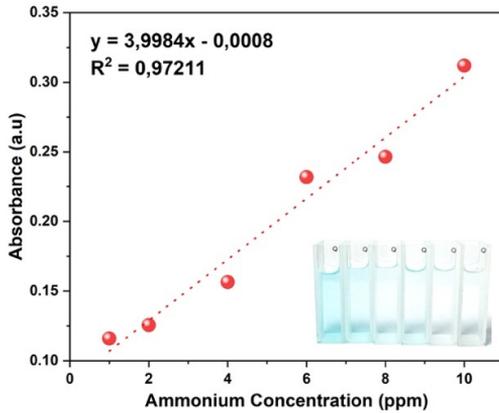


Fig. 3. Indophenol Standard Curve for ammonia at concentrations of 1–10 ppm and fitting results.

imately 0.015 mg/L, confirming sensitivity for aquaculture monitoring.

The established calibration equation is essential for quantifying the amount of ammonium that has been adsorbed by the activated carbon. By measuring the absorbance at 425 nm after treatment with activated carbon, the remaining ammonium concentration in the solution can be accurately calculated using the calibration curve. This approach allows for a precise assessment of the activated carbon's efficacy in adsorbing ammonium ions. The use of Indophenol in this context provides a straightforward and effective method for detecting ammonium, as the reagent produces a visible color change that can be quantitatively measured. The choice of 425 nm as the wavelength for absorbance readings ensures that the measurement captures the peak interaction of the reagent with ammonium, maximizing the accuracy of the results. This calibration curve, therefore, serves as a reliable tool for monitoring the performance of activated carbon in environmental applications, such as water purification, where the removal of ammonium is critical for maintaining water quality stan-

dards [18].

3.3 Determination of ammonia concentration

In aquaculture systems, particularly those employing Recirculating Aquaculture Systems (RAS), maintaining optimal water quality is crucial for the health and productivity of the fish. One of the critical parameters to monitor is ammonia concentration, which can adversely affect fish if it accumulates beyond acceptable levels. To address this issue, carbon filters made from sugarcane bagasse have been utilized to adsorb ammonia, and the effectiveness of these filters can be evaluated by analyzing ammonia concentration over time.

During the first week of monitoring, ammonia concentrations varied across treatments, ranging from 0.008 to 0.034 mg/L. The lowest concentrations were observed in treatments P4 and P5, suggesting that higher activated carbon doses were more effective in reducing ammonia levels compared to P1, P2, and P3. Variations within the same treatment group could be attributed to slight differences in filter performance, initial ammonia load, or operational conditions within the Recirculating Aquaculture System (RAS). By the second week, ammonia concentrations increased across all treatments, ranging from 0.013 to 0.039 mg/L. This rise indicates a possible decline in filter efficiency as adsorption sites become saturated or as ammonia production increases [19, 20]. The highest ammonia levels were recorded in P1, whereas the lowest values were observed in P5, suggesting that higher activated carbon doses maintained better adsorption capacity. In the third week, ammonia concentrations continued to rise, ranging from 0.020 to 0.050 mg/L, reflecting increasing challenges in maintaining low ammonia levels.

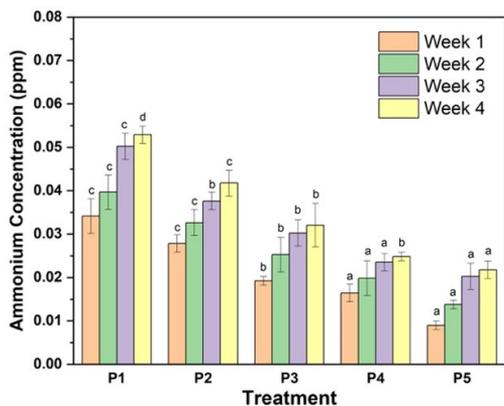


Fig. 4. Ammonium concentration versus variation in activated carbon mass measured over 4 weeks.

The highest concentrations remained in P1, while the lowest persisted in P5. This trend suggests that lower-dose filters were reaching their capacity, leading to reduced effectiveness. By the fourth week, ammonia levels further increased, ranging from 0.021 to 0.052 mg/L. The highest concentrations were consistently recorded in P1, while P4 and P5 exhibited lower levels. These findings indicate that while higher activated carbon doses initially performed better, their efficiency declined over time, likely due to the progressive saturation of the filter material [21].

The observed data reflect a typical scenario in aquaculture where the capacity of adsorption filters can decrease over time as they become saturated with the contaminants they are designed to remove. Activated carbon filters, including those made from sugarcane bagasse, work based on adsorption, where contaminants are held on the surface of the carbon material. As the adsorption sites become occupied, the filter's effectiveness in removing ammonia decreases, leading to increased concentrations in the water [22]. The carbon filters' performance can be influenced by sev-

eral factors. The adsorption capacity of activated carbon is dependent on its surface area and the presence of functional groups that can interact with ammonia molecules. Sugarcane bagasse, a lignocellulosic material, provides a good source of carbon, and its surface properties can be enhanced through activation processes that increase the number of adsorption sites. However, the capacity for ammonia adsorption can be limited by the total surface area and the competition with other substances in the water [23]. In addition to surface area, the pore size distribution of activated carbon plays a significant role in its effectiveness. Micropores, mesopores, and macropores in activated carbon provide different levels of access for ammonia molecules. Smaller pores effectively adsorb smaller molecules, while larger pores enhance ammonia diffusion into the carbon material [24]. The choice of activation conditions, such as the concentration of the activating agent (in this case, NaOH), impacts the pore structure and, consequently, the performance of the carbon filter. The results of this study highlight the importance of regularly monitoring ammonia levels in aquaculture systems and the need for periodic replacement or regeneration of carbon filters. As the filters become saturated, their ability to adsorb additional ammonia diminishes, necessitating maintenance to ensure continued water quality control. Despite the increasing ammonia concentrations over time, the data suggest that activated carbon from sugarcane bagasse retains a considerable adsorption capacity, particularly in higher-dose treatments (P4 and P5). Although the current study did not evaluate filter regeneration, the trend of ammonia removal in the early weeks indicates that the carbon material has potential for reuse. Reactivation through heat treatment or chemical wash-

Table 2. Tilapia growth parameters in aquaculture over 28 days.

Treatment	Absolute Length (cm)	Absolute Weight (g)	Specific Growth Rate (%/Day)	Feed Conversion Ratio (FCR)	Survival Rate (SR) (%)
P1	0.632 ± 0.126 ^a	0.306 ± 0.054 ^a	1.611 ± 0.215 ^a	1.790 ± 0.257 ^d	73.330 ± 11.547 ^a
P2	0.715 ± 0.100 ^{ab}	0.444 ± 0.038 ^b	2.156 ± 0.136 ^b	1.312 ± 0.128 ^c	86.670 ± 5.774 ^b
P3	0.842 ± 0.070 ^{bc}	0.584 ± 0.056 ^c	2.633 ± 0.165 ^{bc}	1.053 ± 0.080 ^b	93.330 ± 5.774 ^{bc}
P4	0.965 ± 0.055 ^{cd}	0.797 ± 0.023 ^d	3.274 ± 0.065 ^c	0.819 ± 0.037 ^{ab}	100.000 ± 0.000 ^c
P5	1.122 ± 0.158 ^d	0.944 ± 0.029 ^e	3.586 ± 0.033 ^c	0.749 ± 0.026 ^a	100.000 ± 0.000 ^c

Note: Values are presented as mean ± standard deviation (SD). Different superscript letters (a, b, c, etc.) indicate significant differences between treatments ($P < 0.05$) based on Duncan's Multiple Range Test (DMRT)

ing could restore its adsorption efficiency, reducing operational costs and making the system more sustainable. Future studies should focus on evaluating the reusability of this activated carbon and optimizing regeneration techniques to prolong its lifespan. In summary, the data from four weeks of monitoring illustrate the performance and limitations of sugarcane bagasse-based carbon filters in removing ammonia from an RAS system. The increasing ammonia concentrations over time indicate a need for careful management of filter usage and potential adjustments to maintain effective water quality management in aquaculture systems.

3.4 Tilapia growth parameters

The analysis of growth parameters for tilapia in various treatments reveals significant differences in performance, indicating the influence of the carbon filters made from sugarcane bagasse on the overall health and efficiency of the aquaculture system (Table 2). Over the course of the experiment, fish in Treatment P5 exhibited the highest absolute length and weight, reaching 1.215 cm and 0.892 g, respectively. This indicates that the fish in this treatment grew more effectively compared to those in the other treatments. Treatment P1, on the other hand, showed the lowest growth metrics, with an absolute length of 0.716 cm and a weight of 0.342 g. The observed growth trends suggest that the higher effectiveness of the carbon filtration in treat-

ments P4 and P5, likely due to better ammonia removal, contributed to enhanced growth performance.

The specific growth rate (SGR), which measures the percentage increase in weight per day, followed a similar pattern, with Treatment P5 achieving the highest SGR of 3.345% per day. This higher SGR reflects more efficient growth under conditions of effective ammonia control, supporting the notion that better water quality enhances fish growth. Conversely, Treatment P1 had the lowest SGR at 1.546% per day, indicating less efficient growth. The improved growth rates in higher treatments suggest that effective ammonia removal positively impacts the metabolic processes of the fish, leading to better growth outcomes[25]. Feed conversion ratio (FCR) is another critical parameter that reflects how efficiently fish convert feed into biomass. The results showed that Treatment P5 had the lowest FCR of 0.892, signifying that the fish in this treatment converted feed into body mass more efficiently than those in other treatments. This low FCR is indicative of optimal conditions provided by the carbon filter, leading to more efficient feed utilization. On the other hand, Treatment P1 had the highest FCR of 1.723, suggesting less efficient feed conversion. The variation in FCR among treatments aligns with differences in ammonia concentrations, where lower ammonia levels in higher treatments likely reduced metabolic

stress and improved feed efficiency. Survival rate (SR), which indicates the proportion of fish surviving the culture period, was highest in treatments P5, both achieving 100%. This high survival rate suggests that these treatments provided the most favorable conditions for the fish, likely due to the effective removal of ammonia and maintenance of water quality [26, 27]. In contrast, Treatment P1 had a lower survival rate of 63.33%, indicating that poorer water quality conditions adversely affected fish survival. The positive correlation between survival rates and treatment effectiveness underscores the importance of efficient ammonia removal in sustaining healthy fish populations [28-30].

4. Conclusion

This study demonstrates the significant impact of activated carbon derived from sugarcane bagasse on the growth performance, feed conversion efficiency, and survival rates of tilapia in recirculating aquaculture systems (RAS). The experimental results indicate that higher carbon masses used in treatment P5 led to enhanced water quality, as evidenced by reduced ammonia levels, which in turn supported better fish growth, lower feed conversion ratios (FCR), and higher survival rates. Specifically, Treatment P5, with the highest carbon mass, showed the most favorable outcomes, achieving the greatest absolute length and weight, the highest specific growth rate (SGR), the lowest FCR, and a 100% survival rate. These findings suggest that the carbon filters' efficiency in ammonia removal played a crucial role in optimizing the fish's metabolic processes, leading to improved overall performance. The study also highlights the mechanisms of ammonium adsorption by the activated carbon, which include physical adsorption, chemi-

cal interactions, and ion exchange. These mechanisms are influenced by several factors, such as pH, temperature, and the presence of competing ions, which affect the adsorption capacity and efficiency. The FTIR analysis further supports the understanding of these interactions, showing how the carbon's surface functional groups contribute to ammonium removal. The research underscores the potential of using sugarcane bagasse as a sustainable and cost-effective raw material for activated carbon production. This not only provides an environmentally friendly solution for managing agricultural waste but also offers significant benefits for aquaculture systems, particularly in maintaining water quality and promoting the health and growth of aquatic organisms. The study's findings can inform future applications of activated carbon in various environmental and industrial contexts, emphasizing the importance of optimizing carbon mass and understanding adsorption dynamics to achieve the best outcomes in water quality management.

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