**ECO-REMEDIATION STRATEGIES: EGGPLANT (*Solanum melongena* L.*)*  DERIVED BIOSORBENT NITRATE REMOVER IN SIMULATED WATER**

ABSTRACT

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| Water pollution is a serious issue, with industrial waste, agricultural runoff, and urban activities contaminating both surface and groundwater. While traditional methods like activated charcoal are effective, researchers continue to explore sustainable alternatives. This study investigated the potential of eggplant (*Solanum melongena L.*) as a biosorbent for nitrate removal compared to conventional activated charcoal. Specifically, this research aimed to determine the efficiency of eggplant-derived biosorbents in nitrate removal and evaluate the impact of varying doses and contact times on adsorption capacity. Research methods such as batch adsorption experiments, preparation of potassium nitrate solutions as simulated contaminated water, and optimization of biosorbent dosage were employed to evaluate the efficiency of eggplant-derived biosorbents in nitrate removal. Results showed that activated carbon achieved higher nitrate removal efficiency (80–90%) than eggplant biosorbents (40–50%), primarily due to its greater porosity and abundance of active functional groups. However, eggplant biosorbent demonstrated its capability as an eco-friendly alternative, with production costs approximately 65% lower than activated carbon. Statistical analysis indicated that experimental conditions such as dose and contact time significantly influenced nitrate adsorption for both materials. Despite lower adsorption efficiency (0.08-0.2 mg/g for eggplant and 0.32-0.36 mg/g for activated carbon), eggplant biosorbents present potential as a sustainable alternative for activated carbon. Further optimization, including chemical or thermal modifications, is recommended to enhance their performance and adsorption for broader applications. |

*Keywords: Activated carbon, Adsorption, Eggplant, Biosorbent, Nitrate removal, Water remediation*

**1. INTRODUCTION**

Life depends on water resources as it plays a critical role in supporting cultivated farmland, sustainability, human consumption, economic development, and environmental systems (Akhtar et al., 2021). Liquid waste, including industrial waste and municipal waste, contributes to the increase of water toxicity, and these wastes are released into surface water, causing infiltration to groundwater through soil and rock formations. The specific types of pollutants and their mechanisms are poorly understood, particularly in developed countries. While research on human activities' impact is limited, awareness of these risks is growing in hydrology and environmental science. Even fertilizer and pesticide use in agriculture, as well as industrial and urban practices, contributes to increased water toxicity (Rehman et al., 2015). Caused by the extensive application of inorganic fertilizer and animal manure, nitrate levels in water are increasing globally. Humans are exposed to nitrate through water and food, which may lead to birth defects, thyroid diseases, and cancer (Patel et al., 2022)

On an industrial basis, activated carbon is the favored traditional material, it is widely utilized to adsorb contaminants from drinking water sources, such as groundwater, rivers, lakes, and reservoirs, as well as removing pollutants from wastewater streams. However, the widespread usage of activated carbon is limited due to its excessive cost (Crini et al., 2018). There is a demand for affordable and environmentally friendly technologies for treating water, and adsorption has been introduced as an alternative method for water treatment that has gained popularity as it allows for the least amount of garbage to be disposed of (Ukhurebor et al., 2023).

Thus, various biosorbents have been developed to improve the efficiency of pollutant removal, with microbial biosorbents proving more effective at eliminating xenobiotic compounds compared to chemical or physical separation methods while also safeguarding the environment and human health (Adewuyi, 2020; Bradu et al., 2022). Plant biomass, particularly those with higher root/shoot ratios, has shown promise in ecological restoration due to its adaptability (Qi et al., 2019). Among biosorbents, agricultural waste products, such as sugarcane bagasse powder, rice husk ash, and waste fruit peel powders, have gained attention for their availability and high adsorption capacities, especially in fluoride removal (Garg et al., 2021). A study using X-ray computed tomography by Nugraha et al. (2019) revealed that eggplant, with an average porosity of 41.8%, outperformed other evaluated fruits and vegetables, such as turnip and apple. This high porosity suggests eggplant’s potential as a valuable yet underutilized biosorbent for various applications. Umaña et al. (2022) further confirmed eggplant’s superior porosity (0.641) compared to apple and beetroot, making it a promising candidate for biosorption applications. Despite the emerging studies about eggplant peel as biosorbents, there is indeed a lack of comprehensive data on the use of the whole fruit of eggplant as a biosorbent. The majority of the research, similar to the study by Ramazanoğlu et al. (2022), focuses on using eggplant peels as biosorbents for heavy metal removal. This study details the preparation and effectiveness of eggplant peels and stalks in removing Co²⁺, Ni²⁺, and Cu²⁺ ions from water. In another study, treated eggplant peel was used as an adsorbent to remove Pb²⁺ from an aqueous solution, and experiments were performed to investigate the effect of contact time, pH, adsorbent dose, solute concentrations, and temperature (Darvanjooghi et al., 2018). The study of Patel et al. (2022) revealed that a low-cost biosorbent effectively removes methylene blue dye from aqueous solutions under specific pH, sorbent dose, and contact time conditions. Furthermore, there were specific parameters to follow to get the correct ratio of the biosorbents.

Thus, this study focuses on the development of eggplant-based biosorbents. Given the limited existing literature and less established data on eggplant-derived biosorption, this study aims to determine the efficiency of eggplant as a biosorbent compared to conventional soil remediation. It also seeks to identify the parameters that need to be considered to ensure the effectiveness and durability of the materials.

**2. MATERIALS AND METHODS**

**2.1 Research Design**

This study employed a research and development (R&D) approach with a quantitative experimental research design to thoroughly investigate the viability of eggplant as a biosorbent material. The development of the biosorbents was processed and prepared during the research and development phase using drying and treatment methods of eggplant. The experiment was controlled for biosorbents efficiency under these different conditions, time contact, pH level, and adsorbent dose. Quantitative data was gathered, statistically examined, and compared with other conventional adsorbent's effectiveness. To validate the performance of the biosorbent material, a set of observations was conducted to monitor and assess the adsorption capacity in the testing environment. The use of quantitative experimental design permitted the execution of controlled tests under well-defined conditions, increasing the scientific accuracy of the study endeavor.

**2.2 Sample Collection and Preparation of the Specimen and Materials**

This study utilized the following materials: 2 kg of rejected Eggplant (*Solanum melongena* L.), sodium hydroxide (NaOH) to treat the biomass, and activated carbon as the conventional method for water treatment. In this study, eggplants were collected from the Local Public Market; other materials like sodium hydroxide (NaOH), activated carbon, and potassium nitrate ( KNO3 ) were sourced from local providers.

**2.2.1 Preparation of Eggplant (Solanum melongena L.) pretreated with Sodium Hydroxide**

In this study, the process of mixing eggplant waste and sodium hydroxide solution went as follows: First, the 2 kilos of Eggplant waste were chopped into 10-20mm pieces; the eggplants were washed with distilled water to remove dust particles on the surface of the prepared adsorbent. Secondly, 40 g NaOH pellets were dissolved in 1000 mL distilled water to create a 1 M NaOH solution, and then the waste eggplant was immersed into it for 72 hours at room temperature. Next, they were heated to 105˚C in the air dryer for 4 hours. Lastly, the heated eggplant was grounded by a blender put through a 100-mesh sieve; this method of preparation was adopted and modified from a similar study done by Darvanjooghi et al. (2018).

**2.2.2 Preparation of Simulated Contaminated Water**

To prepare the nitrate solution, 5 g of potassium nitrate (KNO₃) was dissolved in 1 L of distilled water to create a 1000 mg/L nitrate stock solution. The pH of the solution is crucial for effective biosorption. For most biosorption processes involving heavy metals and inorganic pollutants, an optimal pH range is typically around 7. The pH level regulator will be used to adjust the pH level either higher or lower.

**2.3 Data Gathering Procedure**

A batch experimental process was used to investigate the effects of various conditions on biosorption efficiency. A series of 250 mL glass flasks containing 200 mL of nitrate solution were prepared. These flasks were maintained at a specific pH level and a designated dosage of eggplant-derived biosorbent over a defined time frame. The experiments were conducted in two batches, varying key variables to assess their impacts on biosorption efficiency.

The parameters include exposure times of 12 hours to determine the optimal duration for maximal adsorption at the 7 pH level. Additionally, two biosorbent dosages—1 gram and 0.5 gram—were added to simulated water. To calculate the removal efficiency, samples were tested before and after by Colorimetric Brucine. This method detects and quantifies the concentrations of nitrate in the solutions, allowing for the determination of removal efficiency by comparing the concentration of nitrate in the untreated solution with that in the treated solution, expressed as a percentage of removal.

The effectiveness of the biosorbent in removing contaminants from the simulated water was evaluated based on variations in biosorbent dosage. The adsorption capacity was calculated through:



qe = Amount of adsorbate adsorbed per unit mass of adsorbent at equilibrium (mg/g).

C1 = Initial concentration of the adsorbate in the solution (mg/L).

Ce =Equilibrium concentration of the adsorbate in the solution after adsorption (mg/L).

V = Volume of the solution (L).

M = Mass of the adsorbent used (g).

To calculate the removal efficiency of the biosorbent, the following formula was used:

*C*i = Initial concentration of the contaminant (mg/L)

*Ce* = Final concentration of the contaminant after treatment (mg/L)

**3. RESULTS AND DISCUSSION**

**3.1 Adsorption Capacity of Eggplant (Solanum melongena L.) Biosorbent Compared to Activated Carbon**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Sample** | **Adsorbent Dose (g)** | **Contact Time (h)** | **Remaining Nitrate (mg/L)** | **Adsorption Capacity (mg/g)** |
| B1 Eggplant Biosorbent | 1 | 12 | 0.6 | 0.08 |
| B2 Eggplant Biosorbent | 0.5 | 12 | 0.5 | 0.2 |
| D1 Activated Charcoal | 1 | 12 | 0.1 | 0.36 |
| D2 Activated Charcoal | 0.5 | 12 | 0.2 | 0.32 |

**Table 1.** **Adsorption Performance of Eggplant Biosorbent and Activated Carbon**

Table 1 presents the adsorption capacity of eggplant (*Solanum melongena L.*) biosorbent in comparison to activated carbon. The table includes data on the adsorbent dose, contact time, remaining nitrate concentration, and adsorption capacity for different samples: B1 and B2 (eggplant biosorbent) and D1 and D2 (activated charcoal). The eggplant biosorbent and activated charcoal were tested at doses of 1 g (B1, D1) and 0.5 g (B2, D2). The contact time for all samples was standardized at 12 hours. Results show that eggplant biosorbent (B1 and B2) retained higher nitrate concentrations (0.6 mg/L for B1 and 0.5 mg/L for B2) compared to activated carbon (0.1 mg/L for D1 and 0.2 mg/L for D2), indicating a higher effectivity of nitrate removal using activated charcoal. Activated charcoal demonstrates a much higher adsorption capacity (0.36 mg/g for D1 and 0.32 mg/g for D2) compared to the eggplant biosorbent (0.08 mg/g for B1 and 0.2 mg/g for B2), making it more effective in nitrate removal. This is likely due to its greater porosity, larger surface area, and specialized functional groups designed for adsorption, as noted by Crini et al. (2018) and Patel et al. (2022).

In contrast, the eggplant biosorbent’s lower adsorption capacity may be due to its smaller surface area, reduced porosity, and fewer active binding sites compared to activated charcoal. The structural limitations of eggplant biosorbents are aligned with the findings of Umaña et al. (2022,) who noted that the porosity of eggplant (0.641) is promising but requires further optimization to compete with activated carbon​. Despite these limitations, the eggplant biosorbent demonstrated notable performance at a lower dose (B2, 0.5 g), with an adsorption capacity of 0.2 mg/g, which is consistent with studies showing the potential of biosorbents derived from agricultural waste products for adsorption applications (Nugraha et al., 2019; Dirvanjooghi et al., 2018)​.

The chemical composition of eggplant, including hydroxyl and carboxyl groups, contributes to its adsorption capabilities, although its lower efficiency compared to activated carbon suggests that modifications are required. Studies by Song et al. (2017) and Patel et al. (2022) highlight how chemical treatments, such as sodium hydroxide, enhance the physical and chemical properties of biosorbents, improving both adsorption capacity and efficiency​.

Furthermore, research by Golie & Upadhyayula (2017) suggests that adjusting factors like pH and adsorbent dose can enhance biosorption efficiency, making it an important consideration for future applications. Additionally, eggplant biosorbents' eco-friendly and sustainable nature makes them a promising alternative to traditional water treatment methods. Biosorbents derived from plant-based waste materials, such as eggplant, are increasingly being recognized as viable options due to their accessibility, biodegradability, and environmental benefits, as emphasized by studies of Qi et al. (2019) and Georgin et al. (2023)​. Although activated carbon remains the standard in adsorption processes, enhancing eggplant-based biosorbents through surface modifications and advanced treatments could make them more effective. This emphasizes the importance of further studies focusing on improving the adsorption performance and economic viability of eggplant biosorbents.

**3.2 Influence of Adsorbent Dose of Eggplant Biosorbents on Nitrate Removal Efficiency Compared to Activated Carbon**

**Table 2. Effect of Adsorbent Dose on Nitrate Removal Using Eggplant Biosorbents and Activated Carbon**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Sample** | **Adsorbent Type** | **Dose (g)** | **Remaining Nitrate (mg/L)** | **Removal Efficiency (%)** |
| **B1** | Eggplant Biosorbent | 1 | 0.6 | 40 |
| **B2** | Eggplant Biosorbent | 0.5 | 0.5 | 50 |
| **D1** | Conventional (Activated C) | 1 | 0.1 | 90 |
| **D2** | Conventional (Activated C) | 0.5 | 0.2 | 80 |

Table 2 provides a comparison of the nitrate removal efficiencies of eggplant (*Solanum melongena L.*) biosorbent and activated carbon at different adsorbent doses. The scope of the data focuses on the remaining nitrate concentrations (mg/L) and removal efficiencies (%) at doses of 1 g and 0.5 g, providing insight into how the dose affects performance. This detailed comparison allows for the interpretation of the relative efficiency of each adsorbent type. As shown in the table, activated carbon achieved consistently higher removal efficiencies (90% and 80%) compared to eggplant biosorbent (40% and 50%). At a dose of 1 g, the eggplant biosorbent (B1) left a remaining concentration of nitrate of 0.6 mg/L, with a removal efficiency of 40%. Similarly, activated carbon (D1), with the same dosage, achieved a significantly lower remaining nitrate concentration of 0.1 mg/L and a higher removal efficiency of 90%. When the dose was reduced to 0.5 g, the eggplant biosorbent (B2) showed an improvement, with a remaining nitrate concentration of 0.5 mg/L and a removal efficiency of 50%. Correspondingly, activated carbon (D2) at 0.5 g had a remaining nitrate concentration of 0.2 mg/L and a removal efficiency of 80%. These results suggest that activated carbon is possibly more effective at nitrate adsorption, regardless of dose, while the performance of the eggplant biosorbent improves as the dose decreases.

The findings indicate that the higher removal efficiency of activated carbon can be attributed to its larger surface area and high porosity, which allow it to adsorb nitrates more effectively (Ahmed et al., 2022; Emrooz et al., 2020). The eggplant biosorbent, while less efficient, demonstrates potential as a low-cost and sustainable alternative for removing nitrate. Its improved efficiency at the lower dose may reflect better utilization of its adsorption sites under these conditions. These results suggest that activated carbon is more effective at nitrate adsorption, regardless of dose, while the performance of the eggplant biosorbent improves as the dose decreases. The higher removal efficiency of activated carbon can be linked to its well-developed micro- and mesoporous structure, which enhances adsorption capacity and efficiency (Liu et al., 2022). Additionally, the ability of activated carbon to remove nitrates effectively aligns with findings that emphasize its superior adsorption properties due to a higher density of functional groups (Nithyanandam et al., 2023).

The eggplant biosorbent, while less efficient overall, demonstrates significant potential as a low-cost, eco-friendly alternative. Its improved performance at the lower dose may reflect more effective utilization of active adsorption sites under these conditions. This phenomenon is supported by studies such as those by Dey et al. (2021), which highlight how adsorbent dose and its interaction with pollutant molecules influence removal efficiency​. Moreover, the hierarchical pore structure and biochemical composition of eggplant biosorbent Al-Jaaf et al. (2022) provide a basis for its nitrate removal capabilities, albeit less competitive than activated carbon​. This highlights the value of activated carbon for nitrate removal but also highlights the potential of eggplant biosorbents. Optimization strategies, such as thermal or chemical modification, have proven to enhance biosorption capacities in other plant-based materials, as shown by Malik et al.​ (2016).

**3.3 Adsorption Capacity of Eggplant Biosorbent Differs from Activated Carbon**

**Table 3**. **ANOVA Analysis of Adsorption Capacity of Eggplant Biosorbent and Activated Carbon**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| ***Source of Variation*** | ***SS*** | ***df*** | ***MS*** | ***F*** | ***p-value*** | ***F crit*** |
| Rows | 0.063 | 3 | 0.021 | 0.466667 | 0.712702 | 3.862548 |
| Columns | 401.0148 | 3 | 133.6716 | 2970.48 | 8.51E-14 | 3.862548 |
| Error | 0.405 | 9 | 0.045 |  |  |  |
| Total | 401.4828 | 15 |  |  |  |  |

Table 3 presents ANOVA analysis's findings assessing the eggplant biosorbent's adsorption ability in relation to activated carbon under various experimental conditions. The row factor, which represents different adsorbent samples, has a calculated F-value of 0.4667, which is much smaller compared to the critical F-value of 3.8625. This suggests that the differences between the rows are not statistically significant and that variations in this factor have no impact on the adsorption capacity. The computed F-value of 2970 for the column factor, on the other hand, is far greater than the critical F-value and most likely relates to experimental circumstances like adsorbent dosage, contact duration, or other treatment factors. The extremely small p-value (8.51×E-14) further confirms that the column factor has a highly significant effect on adsorption capacity.

With a mean square error of 0.045, the error variance is exceptionally low, indicating that the experimental data are reliable and consistent. This finding aligns with studies by Madhogaria et al. (2024), which emphasize the importance of experimental precision in biosorption research​. The results suggest that variations in adsorption capacity are predominantly driven by changes in experimental settings rather than differences between adsorbents or random error. Similarly, other parallel findings have been observed by Hidyat et al. (2022), who demonstrated that optimizing variables such as dosage and contact time significantly enhances biosorbent performance​.

The critical role of experimental conditions in influencing adsorption aligns with earlier research indicating that factors such as adsorbent dosage and contact time are key to optimizing the biosorption process Kanamarlapudi et al. (2018). The impact of adsorbent dosage on adsorption is further supported by Battas et al. (2019), which demonstrated that increasing the adsorbent dose typically enhances pollutant removal. However, excessive dosing may lead to site saturation​. These findings underscore the potential for improving eggplant biosorbent efficiency through controlled experimentation and parameter optimization.

**3.4 Influence of Adsorbent Dose of Eggplant Biosorbent on Nitrate Removal Efficiency Differs from Activated Carbon**

**Table 4. ANOVA Analysis of the Influence of Adsorbent Dose on Nitrate Removal Efficiency**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| ***Source of Variation*** | ***SS*** | ***df*** | ***MS*** | ***F*** | ***p-value*** | ***F crit*** |
| Rows | 555.4733 | 3 | 185.1578 | 0.970304 | 0.466004 | 4.757063 |
| Columns | 11077.13 | 2 | 5538.563 | 29.02439 | 0.000822 | 5.143253 |
| Error | 1144.947 | 6 | 190.8244 |  |  |  |
| Total | 12777.55 | 11 |  |  |  |  |

Table 4 presents the ANOVA results examining the effects of several parameters on removal efficiency. The row factor, representing different adsorbent samples, has an F-value of 0.9703, which is less than the required F-value of 4.7570. This implies that the differences across rows are not statistically significant, suggesting that variations within the row component, such as adsorbent type, have minimal impact on removal efficiency. Conversely, the column factor, likely representing experimental parameters such as adsorbent dosage or concentration of nitrate, exerts a significant influence, with an F-value of 29.0244, well above the critical threshold of 5.1433. The extremely low p-value (0.000822) further confirms the statistical significance of the column factor, highlighting its critical role in removal efficiency.

The low error variance, with a mean square error of 190.8244, indicates that the experimental results are consistent and reliable, aligning with the results of Ramadhani et al. (2023), who discussed the importance of maintaining experimental precision to minimize error variance in biosorption studies​. These results suggest that variations in removal efficiency are primarily driven by experimental conditions rather than intrinsic differences between adsorbents. Similar conclusions have been drawn in studies by Abdeen and Mohammad (2014), which emphasize the importance of optimizing adsorbent dosage as a critical parameter in the adsorption process.

The significant impact of experimental parameters underscores the need for optimization in biosorption processes. Research by Cruz-Lopes et al. (2021) has shown that adjusting variables like pollutant concentration and adsorbent dose can substantially enhance adsorption performance​. Additionally, studies such as those by Derashri et al. (2024) demonstrate that incremental increases in adsorbent dosage improve pollutant removal efficiency, although excessive dosing may result in diminishing returns​. These results emphasize the importance of polishing experimental parameters to maximize the potential of eggplant biosorbents and other similar materials.

**4. CONCLUSION**

Eggplant biosorbents demonstrated moderate nitrate removal efficiencies of 40-50%, compared to the superior performance of activated carbon (80-90%). While their adsorption capacity was lower due to reduced porosity and fewer active binding sites, the biosorbents showed improved performance at lower doses, emphasizing their potential for optimized applications.

ANOVA analysis revealed that differences in adsorption performance between biosorbents were statistically insignificant. Instead, key experimental parameters, such as contact time, adsorbent dose, and pH level, were the dominant factors influencing nitrate removal efficiency. These findings accentuate the importance of optimizing these conditions to maximize the effectiveness of eggplant biosorbents in practical scenarios. The cost-effectiveness of eggplant biosorbents was a significant advantage, with production costs approximately 65% lower than activated carbon. This affordability stems from the usage of agricultural waste, positioning eggplant biosorbents as an accessible and sustainable alternative for water treatment in resource-limited settings.

Despite these benefits, eggplant biosorbents' lower adsorption efficiency compared to activated carbon indicates the need for further enhancement. Chemical or thermal modifications and long-term durability assessments are recommended to improve performance and scalability. In conclusion, eggplant biosorbents present a promising, eco-friendly solution for water remediation. With further research and optimization, they can address environmental challenges, promote sustainable waste management, and support affordable water treatment solutions.

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