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Adsorptive Optimization of Abamectin from Aqueous Solutions by Immobilized *Eichhornia crassipes*

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ABSTRACT

Adsorption techniques are frequently used to eliminate particular forms of pesticides. This work aimed to describe the process of adsorbing abamectin (ABM) from aqueous systems onto adsorbents and some factors affecting the process effectiveness. *Eichhornia crassipes,* also known as water hyacinth (WH), was chemically processed utilizing calcium alginate-immobilized WH and sodium alginate as adsorbent. The response surface method (RSM) was implemented to enhance the operational aspects of the adsorption procedure on the removal of ABM residues from aqueous solution. The results show that 95.65% of the abamectin was removed under the optimum conditions of pH = 3, 1000 mg/L of immobilized WH, particle size = 5 µm, shaking speed = 200 rpm, and 30 mg/L of ABM concentration throughout 180 min contact time. The model's predicted response results also show a decent agreement with the experimental data (R^2 = 86.64%), proving the effectiveness of this approach for developing precise predictions. The responses were assessed using a second-order polynomial multiple regression model, which confirmed a successful adjustment with the obtained data using analysis of variance (R^2 = 92.0%, R^2adj = 88.92%, and R^2pred = 82.92%). In conclusion, the results demonstrated the potential application and beneficial adsorption effectiveness of WH in removal of the pesticides from an aqueous solution.

Keywords: adsorption, abamectin, *Eichhornia crassipes*, water hyacinth, response surface methodology, sodium alginate.

INTRODUCTION

Abamectin (ABM), a type of insecticide and acaricide, from the avermectin family is raising concerns about its lasting impact on the environment and potential harm to target organisms. This chemical, known for its properties can cause skin and eye irritation harm the nervous system, and pose environmental risks if inhaled or ingested. The exposure to substances like ABM could result in harm to the lungs, cause chemical burns, neurological impacts, and potentially lasting health complications, like forms of cancer. Therefore, handling and using of this type of harmful chemicals is subject to restricted instructions.

There are several ways that have been applied successfully to remove abamectin from water systems, including adsorption process, reverse osmosis, photo Fenton oxidation, and electrocoagulation. However, among all of these processes, adsorption process is considered as the most cost-effective approach due to simplest setup, low capital cost, and minimal required footprint (Abdulrahman et al., 2018). The utilization of water hyacinth (WH) to remove ABM from aqueous solutions via adsorption process has been applied efficiently (Nafisyah et al., 2022; Salman et al., 2021).

A great deal of recent research work has focused on identifying adsorbents, such as fungi (Bingol et al., 2004), lignin (Šćiban et al., 2011), plants (Zuo et al., 2012), water hyacinth *Eichhorina crassipes* (Li et al., 2013), alginate (Singh and Balomajumder, 2021), algae (Areco et al., 2012), and some other natural materials (Sharma and Bhattacharyya, 2005). These eco-friendly adsorbents are beneficial as they can be conveniently disposed of by incineration once saturated (Li et al., 2013). Water hyacinth, also known as *Eichhornia crassipes*, quickly spreads in water bodies globally raising concerns due to its rapid expansion across continents and countries (Hashem et al., 2020).

This study explored water purification techniques with a focus on extracting a substance from water known as an adsorbent. Since the 1980s, water hyacinth has been utilized to tackle water pollution; it has recently gained recognition for its ability to effectively remove dyes. However, Yerima et al. (2024) studied the photocatalytic degradation processes of Acid Blue Dye using zinc oxide nanoparticles extracted from *Senna siamea* flower (ZnO-S.S.). The removal efficiency of 99% was attained in 150 minutes of contact time with 150 mg of catalyst dosage at an initial acid blue concentration of 10 mg/L. Moreover, Arif et al. (2023) used copper oxide nanoparticles (CuO NPs) extracted from Chenopodium album leaves. The results showed that removal rates of 53.61% and 57% of Abamectin and atrazine after 180 minutes of contact time were achieved, respectively. In another study, phytoremediation of WH was testified for synchronized removal of phenol and cyanide. The removal rate of phenol and cyanide was 96.42% and 92.66% at 300 mg/L and 30 mg/L of pollutants concentration, respectively, in 13 days at pH 8.0 (Singh and Balomajumder, 2021). Researchers have different approaches; some investigate the properties of water hyacinth for adsorption purposes, while others experiment with modified versions of water hyacinth-based adsorbents.

The primary goal was to assess the effectiveness of water hyacinth, in eliminating pollutants from bodies of water. Enhancing the characteristics of a material by immobilizing it in a polymeric structure facilitates easier separation and enables the biomass to be recovered and reused rendering it a favorable method in reactors. Sodium alginate is widely utilized as a matrix for immobilizing biosorbents. The selection of the immobilization platform has an influence, on how immobilized biomass is utilized in environmental settings of immobilized biomass, the mechanical strength and chemical resistance of the particle are influenced by various factors. Lastly, the research considered the following aspects (pH, WH dose, ABM concentration, contact time, particle size, and shaking speed) to examine the removal efficiency of Abamectin by WH.

Materials and methods

Chemicals

The sodium alginate (SA) ($NaC_6H_7O_6$), used in this research was purchased from Special Ingredients Ltd. on Amazon. SA is a powder that can range in color from white to yellow and originates from plants. Abamectin $C_{48}H_{72}O_{14}$(B1a) and $C_{47}H_{70}O_{14}$(B1b) were supplied as a colorless solid by Alpha Chemikaan company, India. In addition to sodium hydroxide, hydrochloric acid, and calcium chloride, were imported by Pan ReacAppliChem ITW Reagents, Spain, from the respective local markets.

Water hyacinth as adsorbent

Water hyacinth was collected from Mosul City's Tigers River bank, cleaned, separated, and dried. The biomass was then compressed and filtered to obtain particle sizes ranging from 63 to 125 μm. The process involved cleaning, drying, and compressing the samples. The cellulose in this aquatic plant, with numerous hydroxyl groups, significantly influences adsorption (Madikizela, 2021). Chemical processing of WH-based adsorbents can increase their surface area, enhancing their adsorption capacity, as the specific surface area directly influences adsorption (Kumar and Chauhan, 2019). The study used sodium alginate to immobilize WH biomass, a biopolymer with potential applications in organic pollutant sorption studies. The resulting alginate biomass slurry was mixed with 0.1 M $CaCl_2$ to create beads with a diameter of 54 mm. The beads were treated, washed twice and kept in $CaCl_2$ at 4 °C, for use (Mahamadi and Mawere, 2014). An orbital shaker was utilized in the research to investigate the absorption of ABM in water solutions. The best absorption conditions were identified by adjusting factors, such as pH levels (3, 5 and 11) stirring speed (100, 200 and 300 rpm) ABM concentration (10, 30 and 60 mg/L) particle size (2, 5 and 8 μm) and WH dosage (0.5–2 g/100 ml). The study assessed how these variables influenced the efficiency of abamectin removal. Equations 1 and 2 were used to calculate the percentages of ABM absorption and elimination (Majlesi and Hashempour, 2017).

$$q_e = (C_0 - C_e)\frac{V}{W} \times 100 \qquad (1)$$

$$Re = \left(\frac{C_0 - C_e}{C_0}\right) \times 100 \qquad (2)$$

where: q_e, solute adsorbed weight, per unit weight of sorbent is measured in milligrams per gram (mg/g). *Re*, removal efficiency is expressed as a percentage (%). The initial concentration of ABM in the solution is denoted by C_0 in milligrams per liter (mg/L) while the final equilibrium concentration of ABM is represented by C_e in milligrams per liter (mg/L). *V* stands for the volume of the solution in liters. W indicates the mass of the adsorbent, in grams.

RESULT AND DISCUSSION

Response surface methodology (RSM) analysis

The research employed design of expert software (DOE) and the Central Composite Design (CCD) to examine how ABM concentration WH dose, shaking speed, particle size, pH and contact time impact adsorption processes through the use of models and regression Equations (Table 1) (Salam et al., 2015).

$$Y = \beta o + \Sigma\beta iXi + \Sigma\beta iiXi2 + \Sigma\beta ijXiXj \quad (3)$$

The study analyzed data using a probability of error (P) value and CCD to optimize the interaction effect of independent components.

Optimization representation

Experiments assessed ABM removal percentage from aqueous solution using CCD as illustrated in Equation 4, creating a regression model using RSM historical data design, modified manually, and obtained the final empirical model (Majlesi and Hashempour, 2017). Figure 1 shows predicted and actual ABM removal percentages, with reasonable correlations. The experimental range was described by the increase in ABM concentration, reduction in removal, and increase in WH dose, as shown in Table 2.

$$\%RE = 76.16 + 0.0481B + 0.7459C - 1.60D + 2.37E + 12.76F - 15.08BC - 7.02C^2 - 5.44D^2 - 11.83E^2 - 14.13F^2 \quad (4)$$

Effect of pH on adsorption

Figure 2 shows that ABM adsorption on immobilized WH at different pH values is significantly influenced by changes in solution

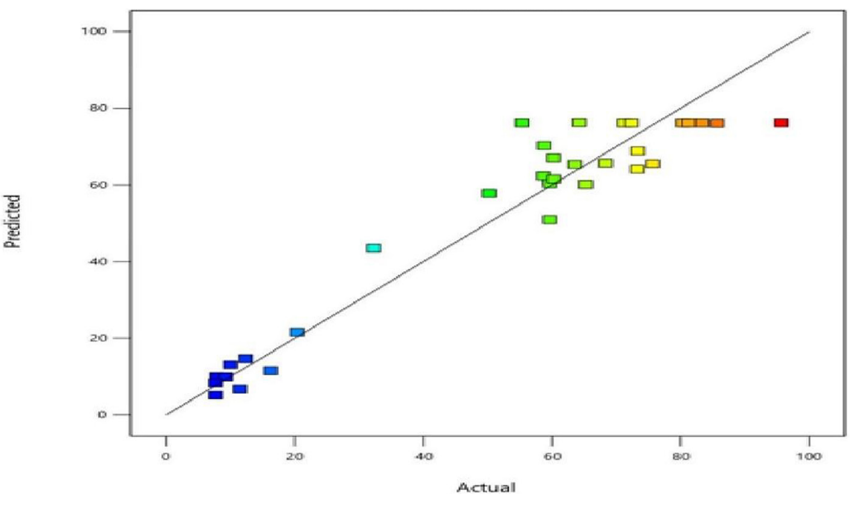

Figure 1. Relation between predicted and actual data of ABM removal

Table 1. Experimental range and levels of the independent variables

Name	Goal	Lower limit	Upper limit	Lower weight	Upper weight	Importance
A: Abamectin concentration	Is equal to 35	10	60	1	1	3
B: Dose of *Eichhornia crassipes*	Is in range	0.5	2	1	1	3
C: pH range	Is in range	3	11	1	1	3
D: Particle size	Is in range	2	8	1	1	3
E: Shaking speed	Is in range	100	300	1	1	3
F: Time	Is in range	5	180	1	1	3
Removal efficiency	Maximize	7.65	95.65	1	1	3

Table 2. Results of experiments according to CCD

Run	ABM conc	Dose of WH	pH range	Particle size	Shaking speed	Contact time	Removal %
1	35	0.0761866	7	5	200	92.5	85.67
2	74.1271	1.25	7	5	200	92.5	83.32
3	10	2	3	8	300	180	68.32
4	60	0.5	11	2	300	180	58.75
5	10	0.5	11	2	100	180	75.65
6	35	1.25	0.739662	5	200	92.5	50.21
7	35	1.25	7	5	356.508	92.5	59.65
8	35	1.25	7	5	200	229.445	60.28
9	35	1.25	7	0.304746	200	92.5	63.54
10	60	2	11	8	100	5	11.45
11	10	0.5	11	8	300	180	60.24
12	35	1.25	13.2603	5	200	92.5	65.23
13	35	1.25	7	5	200	92.5	71.23
14	60	2	3	2	300	180	73.32
15	10	0.5	3	2	100	5	7.65
16	35	1.25	7	5	200	92.5	72.35
17	60	2	3	8	100	180	59.64
18	35	2.42381	7	5	200	92.5	64.23
19	10	0.5	3	8	300	5	9.25
20	60	0.5	3	8	100	5	7.65
21	-4.12711	1.25	7	5	200	92.5	55.32
22	60	0.5	3	2	300	5	9.98
23	35	1.25	7	5	200	92.5	80.35
24	35	1.25	3	5	200	130	95.65
25	10	2	3	2	100	180	73.25
26	60	2	11	2	300	5	12.32
27	60	0.5	11	8	100	180	58.65
28	10	2	11	2	100	5	7.85
29	35	1.25	7	5	200	92.5	81.23
30	35	1.25	7	5	200	-44.4449	20.35
31	10	2	11	8	300	5	16.23
32	35	1.25	7	9.69525	200	92.5	59.65
33	35	1.25	7	5	43.4915	92.5	32.25

pH, as hydrogen ions affect the surface charge of both adsorbents and adsorbate species, resulting in decreased adsorption (Mishra et al., 2021; Liu et al., 2020). The optimal pH value for a solution is 3, as increased positive ions in acidic medium increase hydrogen bonds between charged groups and polymer surfaces. Adsorption increases with decreasing pH due to the attraction forces between positively charged surfaces and pesticides. Surface chemistry theory suggests electrostatic interactions encircle both polymer particles and pesticide molecules (Abdulrahman et al., 2018).

Effect of the initial ABM concentration and contact time on adsorption

The adsorption of ABM on WH at different doses (10, 30, and 60 mg/L), with fixed parameters like WH concentration, pH, shaking speed, and particle size are shown in Figure 3. The maximum ABM removal is at 30.0 mg/L. Adsorption increases significantly between 10 and 30 mg/L, but not at 60 mg/L, as the adsorption sites become saturated (Ali et al., 2016). The optimal concentration of 30 mg/L of ABM was suggested, resulting in 95.65% removal,

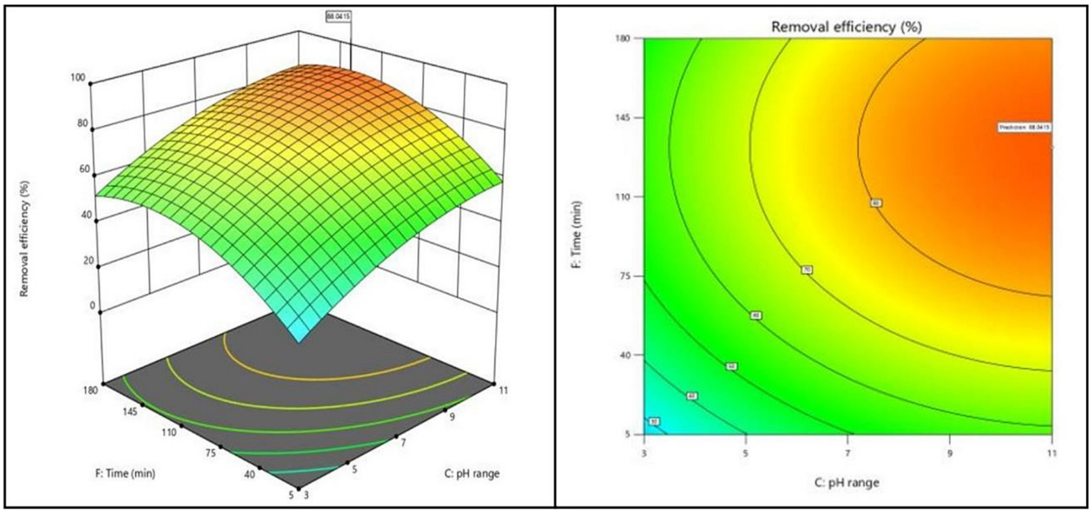

Figure 2. 2D contour plots express and 3D surface plot of pH on removal process

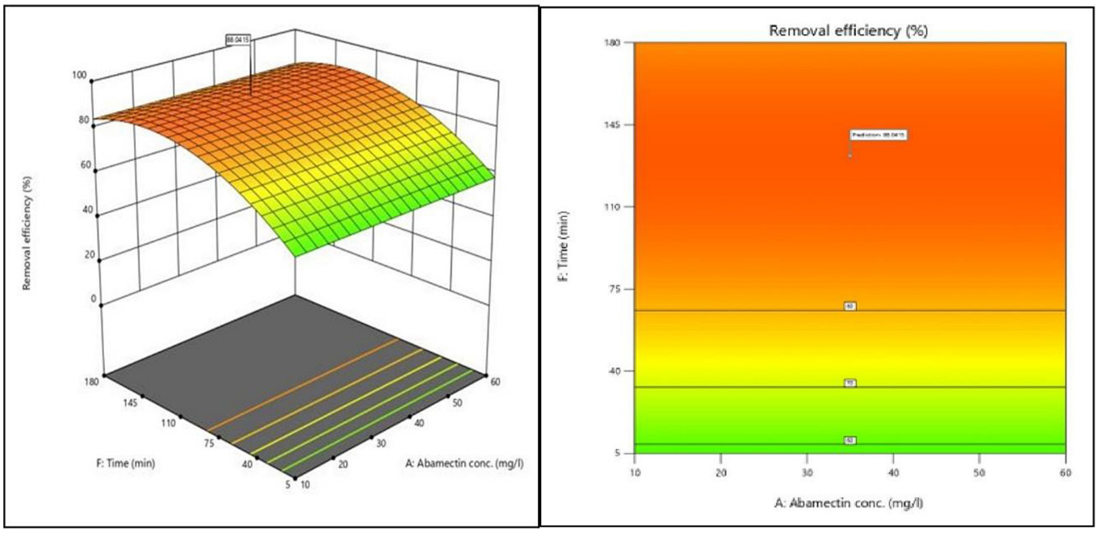

Figure 3. 2D contour plots express and 3D surface plot of ABM concentration on removal process

and longer contact duration did not increase adsorption (Ajala, 2018). Thus, the ideal adsorption time was determined to be 180 minutes.

Effect of WH biomass dosage on adsorption

The adsorption dynamics of ABM on immobilized WH under different doses, with fixed parameters like ABM concentration, pH, shaking speed, and particle size. The biomass dosage is crucial for determining the capacity of the biosorbent for a specific initial concentration (Akbari, 2015). The study examined the impact of adsorbent weight on the efficiency of ABM removal by WH. Results showed that increasing adsorbent weight from 0.5 to 1 g/L increased the percentage of ABM removal to 95.65%, possibly due to more active sites in the solution (Cengiz, 2012; Wanyonyi et al., 2014). As shown in Figure 4, the increase in WH dose leads to a decrease in removal efficiency due to the aggregation of adsorption sites, which reduces intercellular distance and shields binding sites from contaminants (Sayğili and Güzel, 2016). These findings led to the conclusion that the ideal dosage for WH was 1 g/L.

Effect of particle size on adsorption

Figure 4 illustrates the dynamics of ABM adsorption on immobilized (WH) at varying sizes 2.5 µm and 8 µm. The other fixed parameters were ABM concentration (30 mg/L), pH 3, shaking speed (200 rpm), and WH dosage (1 g/L). All adsorption processes depend on the size of the

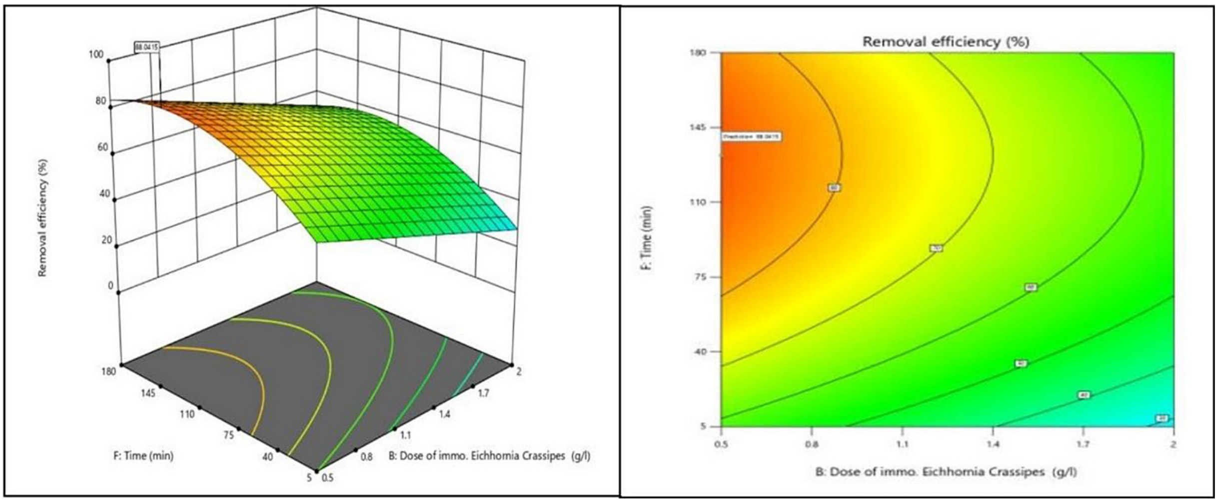

Figure 4. 2D contour plots express and 3D surface plot of immobilized WH biomass amount on removal process

adsorbent particle, since it is a crucial sorption property (Vijayaraghavan and Yun, 2008). The relationship between the sorbent particle size and ABM removal effectiveness is depicted in Figure 5. The results show that the removal effectiveness increased together with the decrease in particle size from 8 to 5 µm. As the particle size decreases, the adsorption rate is relatively greater due to the increasing surface area. Fine particles tend to equilibrate more quickly than larger particles. An increase in the overall surface area probably created more adsorbent adsorption sites (Bai and Abraham, 2001).

Influence of agitation speed on adsorption

The study demonstrates that the removal effectiveness of ABM on immobilized WH increases with agitation speed from 100 to 200 rpm. The agitation speed affects the solute distribution in the bulk solution and the external boundary film. The increased turbulence around the adsorbent particles decreases film resistance to mass transfer, improving efficiency. The results suggest that a 200 rpm agitation speed is adequate for maximal removal by minimizing the boundary layer thickness. Vasanth et al. (2006) and Ong et al. (2007) increased agitation speed enhances adsorption by decreasing film resistance, improving the process. However, higher speeds can cause turbulence and shorten contact time due to the non-homogeneity of sorption mixtures. The vortex phenomena contribute to this non-homogeneity, with 200 rpm being the optimal shaking speed (Parvathiet al., 2007). As a result, 200 rpm will be the optimum shaking speed, as depicted in Figure 6.

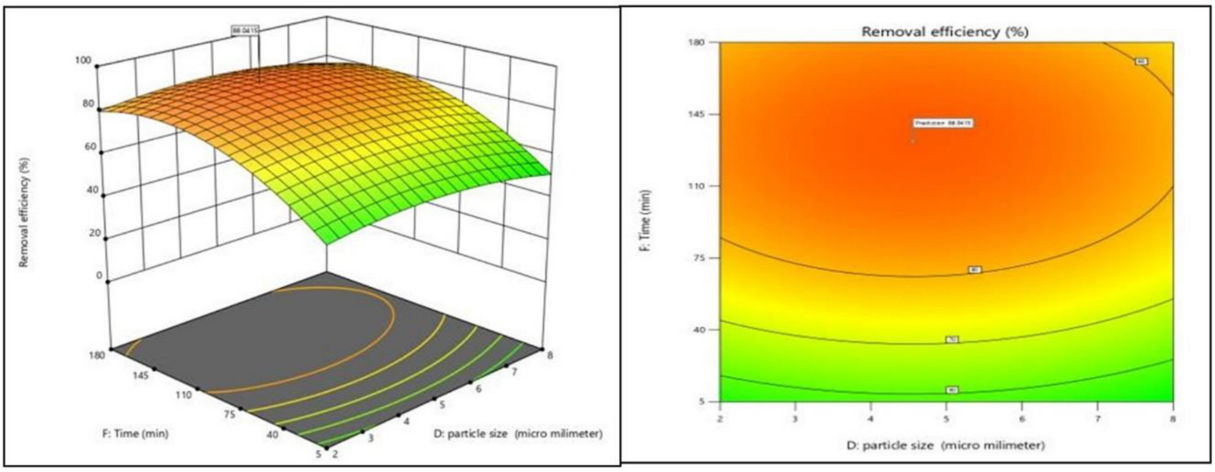

Figure 5. 2D contour plots express and 3D surface plot of particle size on removal process

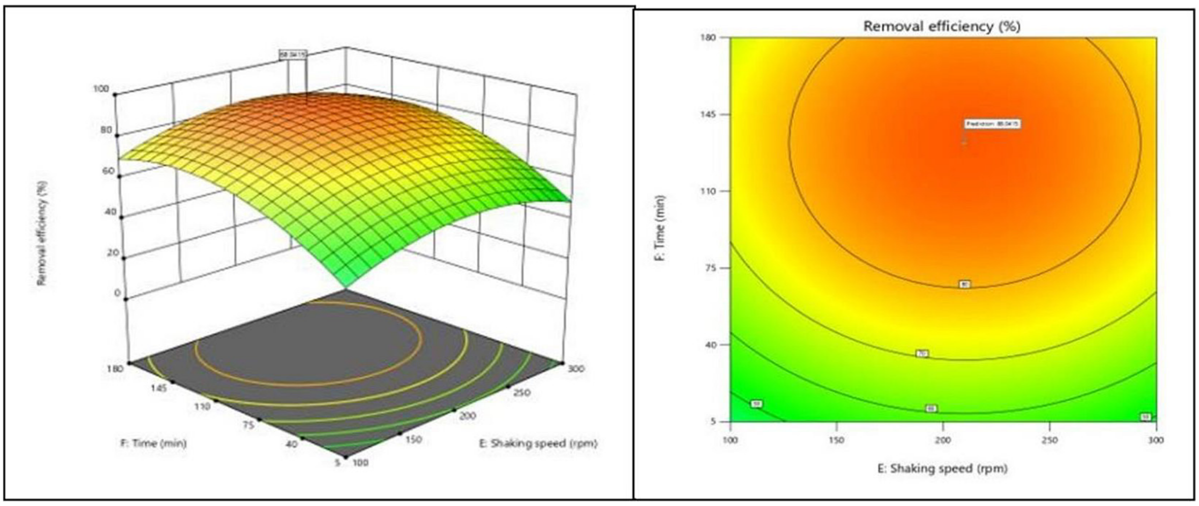

Figure 6. 2D contour plots express and 3D surface plot of agitation speed on the removal process

CONCLUSIONS

The study outlined that immobilized white hyacinth is a cost-effective catalyst for removing insecticides, such as ABM. The low application costs, high production rates, stability under various climatic conditions, and environmental friendliness are the main outputs. Moreover, the flexibility of WH catalytic performance in difficult circumstances i.e. low pH = 3.0 and relatively high dosage of ABM pollutant has new insight for using such adsorbent. The study used response surface methodology to optimize the influence of experimental parameters on ABM removal efficiency. The optimum conditions for attaining a high removal efficiency of 95.65% were found to be an ABM concentration of 30 mg/L, a contact time of 180 minutes, a shaking speed of 200 rpm, a solution pH of 3, and an adsorbent dosage of 1 g/L. In addition, because of its simplicity and efficiency, the immobilized waste could be used often. Additional research is necessary to investigate the effectiveness of WH via other indicators, such as photocatalytic processes, using different forms of pollutants pesticides, insecticides, or dyes as pollutants, and stating water temperature effects.

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REFERENCES

1. Abdulrahman, M.S., Abdulsahib, H.T., Al-luaibi, S.S. 2018. Removal of selected pesticides from aqueous solution using cost effective soft drink bottles, 6(4), 132–137.
2. Ajala, O.J., Nwosu, F.O., Ahmed, R.K. 2018. Adsorption of atrazine from aqueous solution using unmodified and modified bentonite clays. Applied Water Science, 8(7), 1–11. doi:10.1007/s13201-018-0855-y.
3. Akbari, M., Hallajisani, A., Keshtkar, A.R., Shahbeig, H., Ali Ghorbanian, S. 2015. Equilibrium and kinetic study and modeling of Cu(II) and Co(II) synergistic biosorption from Cu(II)-Co(II) single and binary mixtures on brown algae C. indica. Journal of Environmental Chemical Engineering, 3(1), 140–149. doi:10.1016/j.jece.2014.11.004.
4. Ali, I., ALOthman, Z.A., Al-Warthan, A. 2016. Sorption, kinetics and thermodynamics studies of atrazine herbicide removal from water using iron nano-composite material. International Journal of Environmental Science and Technology, 13(2), 733–742. doi:10.1007/s13762-015-0919-6.
5. Amalina, F., Razak, A.S.A., Krishnan, S., Zularisam, A.W., Nasrullah, M. 2022. Water hyacinth (*Eichhornia crassipes*) for organic contaminants removal in water – A review. Journal of Hazardous Materials Advances, 7(August), 100092. doi:10.1016/j.hazadv.2022.100092.
6. Arif, H., Yasir, M., Ali, F., Nazir, A., Ali, A., Al Huwayz, M., Alwadai, N., Iqbal, M. 2023. Photocatalytic degradation of atrazine and abamectin using Chenopodium album leaves extract mediated copper oxide nanoparticles. Zeitschrift für Physikalische Chemie, 237(6), 689–705. doi:10.1515/zpch-2023-0224.
7. Areco, M.M., Hanela, S., Duran, J., dos Santos Afonso, M. 2012. Biosorption of Cu(II), Zn(II), Cd(II) and Pb(II) by dead biomasses of green alga *Ulva lactuca* and the development of a sustainable

matrix for adsorption implementation. Journal of Hazardous Materials, 213–214, 123–132. doi:10.1016/j.jhazmat.2012.01.073.

8. Bai R,S., Abraham, T.E. 2001. Biosorption of Cr (VI) from aqueous solution by *Rhizopus nigricans*. Bioresource Technology, 79(1), 73–81. doi:10.1016/S0960-8524(00)00107-3.
9. Bingol, Az., Ucun, H., Bayhan, Y.K., Karagunduz, A., Cakici, A., Keskinler, B. 2004. Removal of chromate anions from aqueous stream by a cationic surfactant-modified yeast. Bioresource Technology, 94(3), 245–249. doi:10.1016/j.biortech.2004.01.018.
10. Cengiz, S., Tanrikulu, F., Aksu, S. 2012. An alternative source of adsorbent for the removal of dyes from textile waters: *Posidonia oceanica* (L.). Chemical Engineering Journal, 189–190, 32–40. doi:10.1016/j.cej.2012.02.015.
11. Kumar, P., Chauhan, M.S. 2019. Journal of environmental chemical engineering adsorption of chromium (VI) from the synthetic aqueous solution using chemically modi fi ed dried water hyacinth roots. Journal of Environmental Chemical Engineering, 7(4), 103218. doi:10.1016/j.jece.2019.103218.
12. Liu, C., Ye, J., Lin, Y., Wu, J., Price, G.W., Burton, D., Wang, Y. 2020. Removal of cadmium (II) using water hyacinth (*Eichhornia crassipes*) biochar alginate beads in aqueous solutions. Environmental Pollution, 264, 114785. doi:10.1016/j.envpol.2020.114785.
13. Madikizela, L.M. 2021. Removal of organic pollutants in water using water hyacinth (*Eichhornia crassipes*). Journal of Environmental Management, 295(March), 113153. doi:10.1016/j.jenvman.2021.113153.
14. Mahamadi, C., Mawere, E. 2014. High adsorption of dyes by water hyacinth fixed on alginate. Environmental Chemistry Letters, 12(2), 313–320. doi:10.1007/s10311-013-0445-z.
15. Majlesi, M., Hashempour, Y. 2017. Removal of 4-chlorophenol from aqueous solution by granular activated carbon/nanoscale zero valent iron based on Response Surface Modeling. Archives of Environmental Protection, 43(4), 13–25. doi:10.1515/aep-2017-0035.
16. Mishra, S., Cheng, L., Maiti, A. 2021. The utilization of agro-biomass/byproducts for effective bio-removal of dyes from dyeing wastewater: A comprehensive review. Journal of Environmental Chemical Engineering, 9(1), 104901. doi:10.1016/j.jece.2020.104901.
17. Ong, S.T., Lee, C.K., Zainal, Z. 2007. Removal of basic and reactive dyes using ethylenediamine modified rice hull. Bioresource Technology, 98(15), 2792–2799. doi:10.1016/j.biortech.2006.05.011.
18. Parvathi, K., Nagendran, R., Nareshkumar, R. 2007. Lead biosorption onto waste beer yeast by-product, a means to decontaminate effluent generated from battery manufacturing industry. Electronic Journal of Biotechnology, 10(1). doi:10.2225/vol10-issue1-fulltext-13.
19. Sahoo, D., Awasthi, A., Dhyani, V., Biswas, B., Kumar, J., Reddy, Y.S., Adarsh, V.P., Puthiyamadam, A., Mallapureddy, K.K., Sukumaran, K.K., Ummalyma, S.B., Bhaskar, T. 2019. Value-addition of water hyacinth and para grass through pyrolysis and hydrothermal liquefaction. Carbon Resources Conversion, 2(3), 233–241. doi:10.1016/j.crcon.2019.08.001.
20. Salam, K., Agarry, S., Arinkoola, A., Shoremekun, I. 2015. Optimization of operating conditions affecting microbiologically influenced corrosion of mild steel exposed to crude oil environments using response surface methodology. British Biotechnology Journal, 7(2), 68–78. doi:10.9734/bbj/2015/16810.
21. Sayğili, H., Güzel, F. 2016. Effective removal of tetracycline from aqueous solution using activated carbon prepared from tomato (*Lycopersicon esculentum* Mill.) industrial processing waste. Ecotoxicology and Environmental Safety, 131, 22–29. doi:10.1016/j.ecoenv.2016.05.001.
22. Singh, N., & Balomajumder, C. (2021). Phytoremediation potential of water hyacinth (*Eichhornia crassipes*) for phenol and cyanide elimination from synthetic/simulated wastewater. Applied Water Science, 11(8), 144. https://doi.org/10.1007/s13201-021-01472-8.
23. Srivastava, A., Jangid, N.K., Srivastava, M. 2018. Pesticides as water pollutants, (September). doi:10.4018/978-1-5225-6111-8.ch001.
24. Vasanth Kumar, K., Ramamurthi, V., Sivanesan, S. 2006. Biosorption of malachite green, a cationic dye onto *Pithophora* sp., a fresh water algae. Dyes and Pigments, 69(1–2), 102–107. doi:10.1016/j.dyepig.2005.02.005.
25. Vijayaraghavan, K., Han, M.H., Choi, S.B., Yun, Y.S. 2007. Biosorption of reactive black 5 by *Corynebacterium glutamicum* biomass immobilized in alginate and polysulfone matrices. Chemosphere, 68(10), 1838–1845. doi:10.1016/j.chemosphere.2007.03.030.
26. Vijayaraghavan, K., Yun, Y.S. 2008. Bacterial biosorbents and biosorption. Biotechnology Advances, 26(3), 266–291. doi:10.1016/j.biotechadv.2008.02.002.
27. Wanyonyi, W.C., Onyari, J.M., Shiundu, P.M. 2014. Adsorption of congo red dye from aqueous solutions using roots of *eichhornia crassipes*: Kinetic and equilibrium studies. Energy Procedia, 50, 862–869. doi:10.1016/j.egypro.2014.06.105.
28. Yerima, E.A., Ogwuche, E., Ndubueze, C.I., Muhammed, K.A., Habila, J.D. 2024. Photocatalytic degradation of acid blue 25 dye in wastewater by zinc oxide nanoparticles. Trends in Ecological and Indoor Environment Engineering, 2(1), 50–55. doi:10.62622/TEIEE.024.2.1.50-55.
29. Zhang, Y., Kogelnig, D., Morgenbesser, C., Stojanovic, A., Jirsa, F., Lichtscheidl-Schultz, I., Keppler, B.K. 2011. Preparation and characterization of immobilized [A336][MTBA] in PVA-alginate gel beads as novel solid-phase extractants for an efficient recovery of Hg (II) from aqueous solutions. Journal of Hazardous Materials, 196, 201–209. doi:10.1016/j.jhazmat.2011.09.018.