NanoWorld Journal

https://doi.org/10.17756/nwj.2023-114

Research Article

Open Access

Catalytic Activity of Nanocomposite: Synthesized Electrochemical Sludge using Iron Electrodes and Marine Algae (Fe_3O_4/marine algae NP) for the Degradation of Emerging Pollutant Malathion

Vykuntam Supriya*, **Venkata Rao Poiba and Meena Vangalapati**

Department of Chemical Engineering, Andhra University College of Engineering, Visakhapatnam, Andhra Pradesh, India

***Correspondence to:**
Vykuntam Supriya
Department of Chemical Engineering,
Andhra University College of Engineering,
Visakhapatnam, Andhra Pradesh, India.
E-mail: supriya.vykuntam24@gmail.com

Received: March 17, 2023
Accepted: April 03, 2023
Published: April 10, 2023

Citation: Supriya V, Poiba VR, Vangalapati M. 2023. Catalytic Activity of Nanocomposite: Synthesized Electrochemical Sludge using Iron Electrodes and Marine Algae (Fe_3O_4/marine algae NP) for the Degradation of Emerging Pollutant Malathion. *NanoWorld J* 9(2): 29-36.

Published by United Scientific Group

Abstract

Numerous studies on pollutant removal and the application of various electrochemical technologies have already been conducted in the area of electrocoagulation (EC). Sludge, a waste product of the EC process, results in higher operational expenses associated with waste disposal. Sludge includes valuable materials like nutrients or metals removed during water purification in addition to metals from the electrodes used in an EC system, like aluminum or iron. For the removal of phosphate by electrocoagulation using iron electrodes, the effects of various operational parameters including, electrolysis duration (25 min), voltage (10 V), pH (7.0), NaCl concentration (2 g/L), and electrode spacing (3 cm) were found to be the most effective for optimizing phosphates by EC. The maximum amount of phosphorus removed under these ideal circumstances is 93.94%. One of the most widely used pesticides in the globe is organophosphate. Malathion, which is one of them and is categorized as carcinogenesis, needs to be properly eliminated because it is widely used and has a lot of pathogenicity. The primary purpose of this study is to reuse the sludge and synthesize with marine algae to produce nanoparticles (NP) for the degradation of malathion. The parameters are agitation time (30 min), pH (7), catalyst dosage (0.1 g/L) at 318 K, the degradation of malathion is (98.85%). Studies on kinetic, isothermal, and thermodynamic processes have produced the greatest outcomes. For the samples collected, scanning electron microscope (SEM), X-ray diffraction (XRD) and Fourier transform infrared (FTIR) analysis has been carried out. The goal of the current research is to degrade malathion using Fe_3O_4/marine algae NP. The effects of independent variables such as pH, catalyst dosage, and agitation time on malathion degradation effectiveness have been examined based on experimental data using the Response Surface Methodology (RSM) by Box-Behnken Design (BBD).

Keywords

Electrocoagulation, Sludge, Iron electrode, Malathion, Marine algae, Fourier transform infrared spectroscopy, Scanning electron microscope, Box-Behnken design

Introduction

Wastewater is created from a variety of sources, including residential, institutional, industrial, commercial, and agricultural and it includes a number of pollutants that disturb the natural equilibrium of the environment. The concentration of soluble forms of phosphorus compounds in aquatic environments has significantly grown as a result of human activities over the past 50 years, which have seen an increase in the use of detergents, chemical fertilizers, animal dung, wastewater effluents, and plant residues. Soluble phosphorus can affect the sustainability and purity of water bodies and cause eutrophication and other environmental problems. This condition can result in a decrease in water oxygen levels due to the breakdown of algae, putting fish and other aquatic life in danger and decreasing biodiversity [1, 2]. The process of eutrophication, also referred to as the overgrowth of large aquatic plants and algae, can be triggered by an overabundance of phosphorus. Algal blooms brought on by high phosphorous levels have the potential to produce toxins that are harmful to both human and animal health. The ability of EC treatment methods to remove a variety of contaminants, including heavy metals, organic matter, oils, suspended particles, dissolved particles, and various chemical compounds, has sparked researchers' interest [3]. The majority of these studies have concentrated on the elimination of various elements, including metals, pharmaceuticals, and nutrients. Global recycling demand has been rising, and environmental regulations for all waste goods are getting stricter everywhere. Therefore, it is crucial to create technologies that will reduce the amount of waste that is dumped in landfills. Studies on sludge valorization are crucial because although EC purifies water, it also produces gases and sludge that could be regarded as trash. There hasn't been much research done on the potential applications of EC waste, and there haven't been many studies on its use or value in particular industries. There have been a few studies on the use of sewage as catalysts, absorbents, pigments, building materials, and fertilizers [4-11]. EC produces less sludge than conventional chemical precipitation. The amount of sludge varies depending on the technique and element being purified. They discovered that a larger sludge volume was correlated with a longer reaction time and an increasing pH or current density [12]. EC is a technique that produces low volume of sludge, which primarily consists of metallic oxide/hydroxide. As a result, EC sludge is simple to dewater, and it settles easily. EC flocs are also bigger than chemical precipitation flocs and the sediment has less water in it [13]. EC sludge is stable and robust to acids. Additionally, obtaining it through filtering is simple [14]. Materials based on iron oxide are frequently used catalysts and have a variety of uses. Materials based on iron oxide may be present in EC wastewater. EC sludge and discovered that because of its high metal concentration, this sludge can be used as a catalyst. They did not perform any quantitative analyses to support this theory; they only mentioned it in terms of the qualities that make the sludge appropriate for catalytic use [15].

Based on the structure of the pigments and the structure of the cells, they are divided into numerous groups. However, the three groups are green algae, brown algae, and red algae, make up the majority of the categorization. Algae come in a variety of forms and sizes. Algae can also develop on rocks, moist soil, and tree bark in addition to aquatic areas. Algae use photosynthetic processes to develop and survive, so they require moisture and sunlight. The science of nanotechnology, which involves creating structures at the nanoscale, is advancing and will eventually achieve its pinnacle. The synthesis of NP is one of the key results of nanotechnology [16]. Nowadays, biological elements like bacteria, fungi, algae, and plants are used to create NP. This process, also known as "green synthesis," is risk-free, affordable, environmentally friendly, and the sources are widely accessible [17].

These creatures have enzymes that can convert metal ions into metallic NP [18]. The synthesis of NP from algae is a bottom-up process. Some of the most common NP created using algae include gold, silver, copper oxide, and zinc oxide. First, algal extracts are made, ideally aqueous or ethanolic extracts. Algae decrease the metal ions and create metallic NP when the extracts are combined with a particular metallic solution (specific to the kind of NP required). The electrostatic contact between the positively charged functional groups or peptides in the algae and the negatively charged ions in the metallic solution causes the reduction [19]. Through irrigation and precipitation, pesticides used in agriculture can enter surface water bodies, causing pollution of those waterways. Malathion [(2dimethoxyphosphorothioyl) sulfanyl], one of these herbicides, is widely employed. Pesticides are extensively used to both control diseases spread by arthropods and raise the productivity of agricultural products. Due to their effects on cholinesterase activity and central nervous system disorders, organophosphorus pesticides like malathion are regarded as a significant danger to human health. Malathion is highly soluble in water, making it challenging to remove using traditional treatment methods like sand filtering and coagulation. Several techniques, including photocatalytic degradation, biological oxidation, advanced oxidation processes, and adsorption, have been used to get rid of these poisons. Adsorption is a desirable strategy for removing pesticides from these others. The adsorption technique is a popular choice because it is easy to use, dependable, secure, affordable, and environmentally friendly.

However, there are very few studies available for valorization of EC sludge as catalyst. In an attempt to investigate the degradation of malathion using iron oxide/marine algae NP (Fe_3O_4/marine algae NP) as a catalyst in degradation process, the current study used the BBD technique to analyze the data.

Materials and Methods

Malathion (50% EC) is purchased from Katyayani Organics & imports, India and Disodium Phosphate are used to prepare stock solutions. Ammonium molybate, Potassium antimony tartrate, ascorbic acid chemicals are used as reagents for determination of phosphate and malathion from aqueous solution. For malathion estimation reagents used are copper sulfate, carbon tetrachloride, ethyl alcohol, and sodium sulphate. Double distilled water was used to prepare all the estimation solutions. All the chemicals are purchased from Lotus Enterprises Private Ltd., Visakhapatnam, India.

Equipment's

The concentration of phosphates and malathion was measured using an ultraviolet-visible (UV-Vis) spectrophotometer (model number 2203), DC-power supply voltmeter, the pH of the phosphates and malathion solution was measured using a digital pH meter (model number 335), the temperature was maintained using a temperature-controlled orbital shaker (model number KEMI India), and the solids were separated using a centrifuge (model R-8C) from REMI India. The samples were dried using a hot air oven that was bought from optics technology India. Stirrer with heating plate, REMI 1MLH, India, used for synthesis of NP.

EC parameters and sludge preparation

For each run, a known volume of sodium chloride, acting as a conductor, was added to a liter of phosphate solution. The liquids were poured into the electrolytic cell. The pH was altered by introducing solutions of HCl and NaOH. Direct current from the DC-power source was passed through the solution by the four electrodes during the electrolysis run time. In the present study, phosphate was eliminated using an EC method with iron plate electrodes. Samples were collected at set intervals. Phosphates were measured in the solution using a UV-Vis spectrophotometer. It investigated how to make process variables like electrolysis duration, NaCl concentration, pH, voltage, and initial concentration as efficient as possible. The removal obtained was 93.94% and the sludge is centrifuged and dried for 2 hours at 100 °C.

Synthesis of Fe_3O_4/marine algae NP catalyst

The sludge was obtained from the EC process and stored in dry container. Marine algae was collected on rocks from the sea. It is cleaned with distilled water for the removal of external material. Algae was dried under the sunshade for 72 hours, until it is moisture free. Dried algae was stored in different containers which were air tight. The sludge, which is $Fe_3(PO)_4$ based, and algae powder is taken in the ratio 1:5 in distilled water and kept on magnetic stirrer for 5 hours at room temperature. Later it is dried at 100 °C for 4 hours and grinded into powder and stored in a container. The prepared Fe_3O_4/marine algae NP are used for the degradation of malathion as catalyst.

Characterization of sludge and Fe_3O_4/marine algae NP

SEM analysis

The SEM analysis has been obtained for EC sludge in figure 1, where the iron metal oxide is more in the sludge along with other elements. Small globular structure displays sludge after calcination in a SEM image. The morphology and texture of sludge reveal agglomerated particles together with high compaction. The size of particles formed was around 30 - 70 nm in which Fe_3O_4/marine algae NP. The average sludge crystal size was 49.81 nm, supporting the findings of the SEM study and peak heights observed at positions (2θ) and d-values for Fe_3O_4/marine algae NP in figure 4. The average catalyst crystal size was 40.26 nm. The acquired reflections are clear and intense, indicating that the synthesized NP structures are crystalline and small in size.

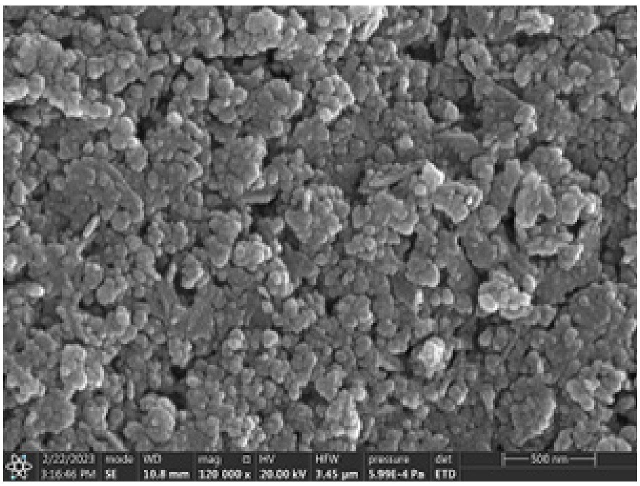

Figure 1: SEM image of EC sludge.

Results and Discussion

Experimental data are generated in a batch mode of operation to study the effect of various parameters for the degradation of malathion from the aqueous solution using Fe_3O_4/marine algae NP powder as catalyst. The effect of various parameters was studied on the degradation of malathion. Various experimental runs are conducted in the present study and the following parameters were evaluated.

Effect of agitation time

It is found from the plot in figure 5 that the % degradation is gradually increased in the first 5 min of agitation. Beyond the agitation time of 30 min, the % degra-

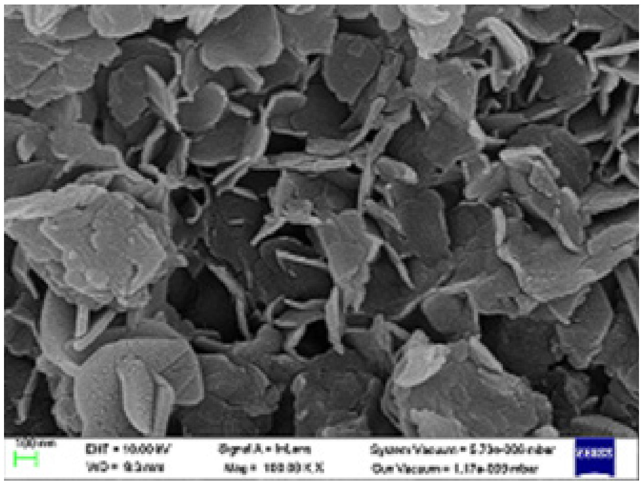

Figure 2: SEM image of Fe_3O_4/marine algae NP.

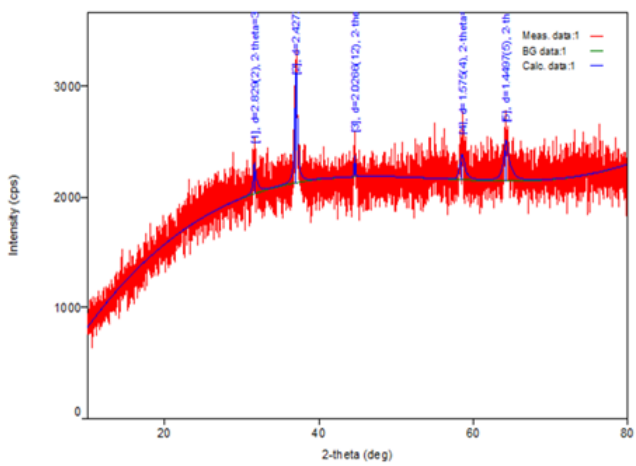

Figure 3: XRD image of EC sludge.

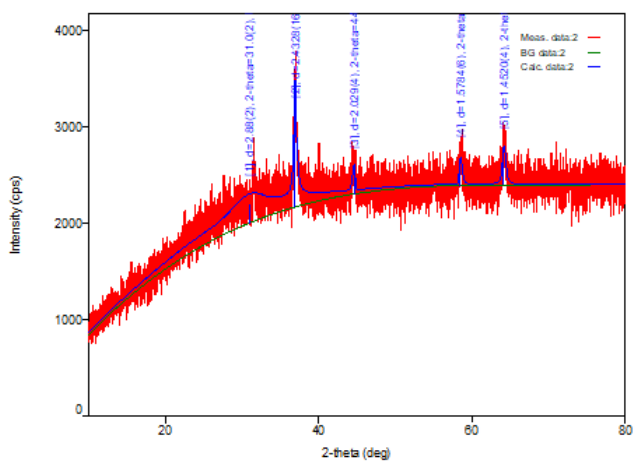

Figure 4: XRD image of Fe_3O_4/marine algae NP.

dation decreases. So, the equilibrium agitation time is 30 min. The rate of percentage degradation is higher in the initial stages because adequate surface area of the catalyst is available for the degradation of malathion. As time increases, substrate deactivation takes place and removal decreases.

Effect of initial concentration of malathion

A plot is drawn in figure 6 between % degradation of malathion and pH of aqueous solution. A significant increase in percentage degradation of malathion is observed as pH is increased from 4 to 7 and downward trend of the % degradation is noted with a decrease in pH above 7. For a typical experiment with 50 ml of aqueous solution, adding a catalyst dosage of 0.1 g/L, the extent of degradation is increased from 59.42% to 82.48% in the pH range from 4 to 7.

Effect of pH in aqueous solution

The effect of initial concentration of malathion in the aqueous solution on the percentage degradation at equilibrium agitation time is shown in figure 7. The % degradation is gradually decreased from 98.85% to 59.82% by increasing malathion concentration from 10 to 100 mg/L. Lesser percentage of malathion is degraded for higher concentration of malathion in the aqueous solution.

Effect of catalyst dosage

Figure 8 represents the variation in percentage degradation of malathion from the aqueous solution with catalyst dosage. The % degradation is increased from 30.32% to 82.48% as dosage is increased from 0.02 to 0.1 g/L. The % degradation from the aqueous phase decreases from 82.48% to 23.34% with an increase in the dosage amount from 0.1 to 0.18 g/L. This is so because with less amount of catalyst, the amount of malathion is much more such that there were not enough surfaces where malathion could bind on to. While at higher catalyst concentration, all available sites were not utilized causing agglomeration of the catalyst which in turn decreases the amount of adsorption sites available. Hence

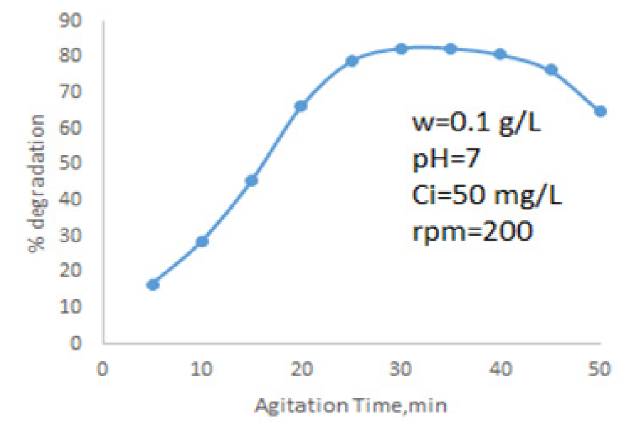

Figure 5: Effect of agitation time on % degradation of malathion.

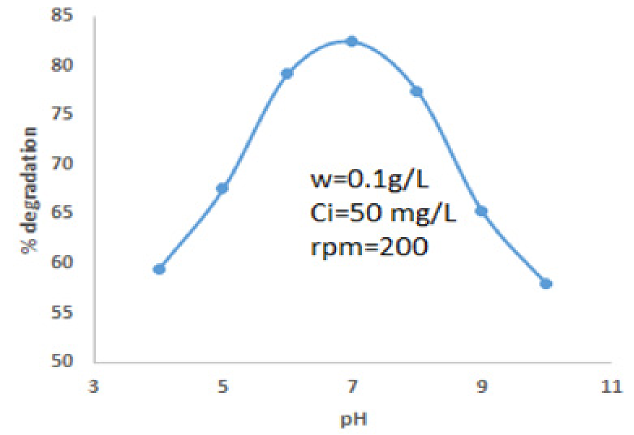

Figure 6: Effect of pH on % degradation of malathion.

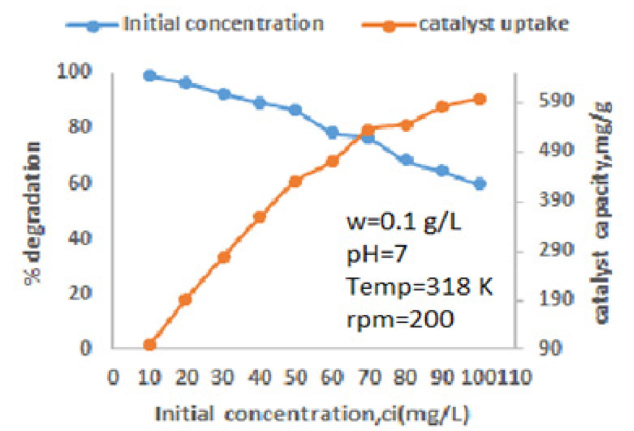

Figure 7: Effect of initial concentration on % degradation of malathion and on catalyst capacity.

all other experiments are conducted at a dosage of 0.1 g/L.

Effect of temperature

The effect of changes in the temperature on the Fe_3O_4/marine algae NP is shown in figure 9. Results indicate that the adsorption capacity of Fe_3O_4/marine algae NP for the malathion increased with temperature. This may be a result of an increase in the mobility of the catalyst with temperature. An increasing number of molecules may also require sufficient en-

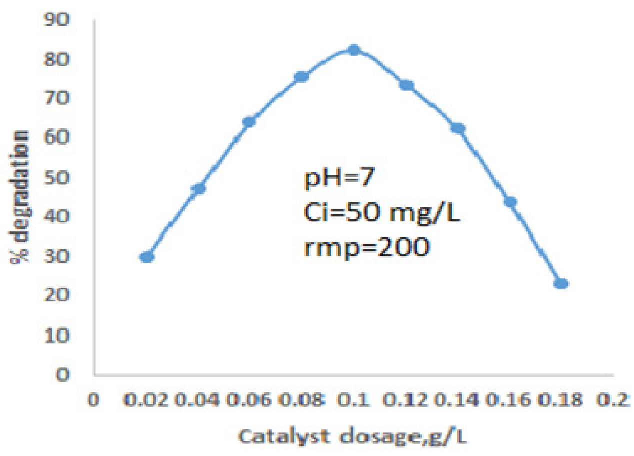

Figure 8: Effect of catalyst dosage on % degradation of malathion.

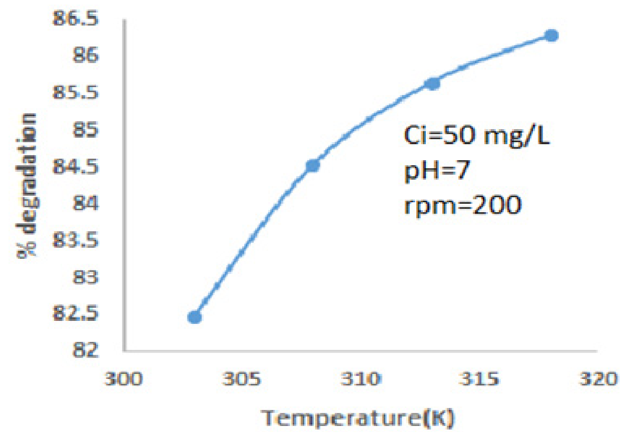

Figure 9: Effect of temperature on % degradation of malathion.

ergy to undergo an interaction with active sites at the surface. Furthermore, increasing temperature may produce a swelling effect within the internal structure of the Fe_3O_4/marine algae NP enabling large molecules to penetrate further. The maximum degradation of malathion has been observed at 45 °C and minimum degradation of malathion has been observed at 30 °C.

Kinetics and thermodynamics studies

The two different kinetic models that were employed to interpret the adsorption data are shown in table 1. Pseudo-second order models (R^2 = 0.9937) fit the experimental data better than pseudo-first order models shown in figure 10 and figure 11. They describe homogeneous and heterogeneous surface adsorption as well as monolayer and multilayer adsorption under various non-ideal conditions. The Gibbs free energy (ΔG°) used to determine the thermodynamic energy and is endothermic in nature shown in figure 12 and in table 2.

FTIR analysis

The analysis is done to identify the active groups for before in figure 13a and after degradation process of the catalyst in figure 13b. The area 1633.47, 1656 cm^{-1} in the spectrum of malathion-loaded catalyst was covered by a weak intensity broadband, which denotes a significant concentration of SiO and POC groups. Minimal broadbands at 3,480 and 3,537 cm^{-1} might be a sign of an H-bonded water bridge's hydroxyl groups. Minor bands between 3,665.86 and 3,391.67 cm^{-1} are open -OH group. The spectrum of malathion-loaded catalyst almost completely lacked characteristic bands in the area 1111.11 cm^{-1} related to the $-CH_3$ and $-CH_2$ groups of malathion spectrum. The peaks seen at 480 - 510 cm^{-1} are two strong vibrations seen due to Fe-O band present in the nanocomposite.

RSM analysis

The investigation of statistically created combinations aimed at maximizing the desired response, the estimation of coefficients by fitting experimental data to response functions, the prediction of response using the created regression model and the evaluation of the model's suitability are all included in the optimization of process parameters using RSM. The

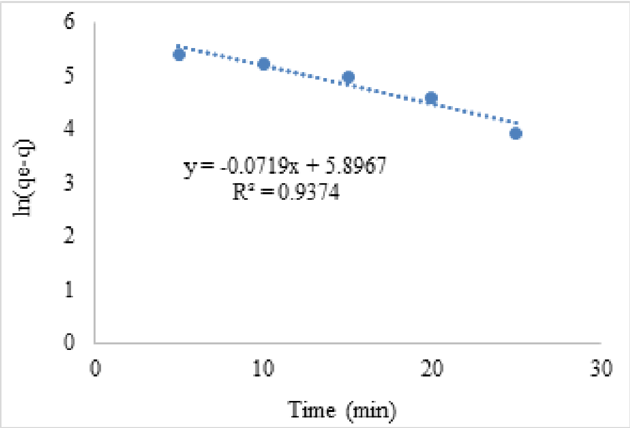

Figure 10: Pseudo-first order.

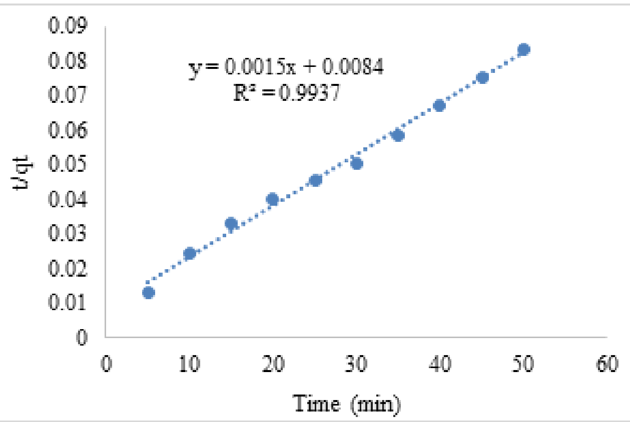

Figure 11: Pseudo-second order.

Table 1: Kinetic equations and rate constant.

Order	Equation	Rate constant	R^2
Lagergren first order	log (qe-qt) = -0.0719 t + 5.8967	0.0.0528 min^{-1}	0.9374
Pseudo second order	t/qt = 0.0015t + 0.0084	0.267 g/(mg-min)	0.9937

Table 2: Thermodynamic studies.

Temperature, K	Fe_3O_4/marine algae NP		
	ΔG0 (kJ/mol)	ΔH0 (kJ/mol)	ΔS0 (J/mol.K)
303	-6394.95	99.52	288.96
308	-7119.46		
313	-8495.83		
318	-11775.3		

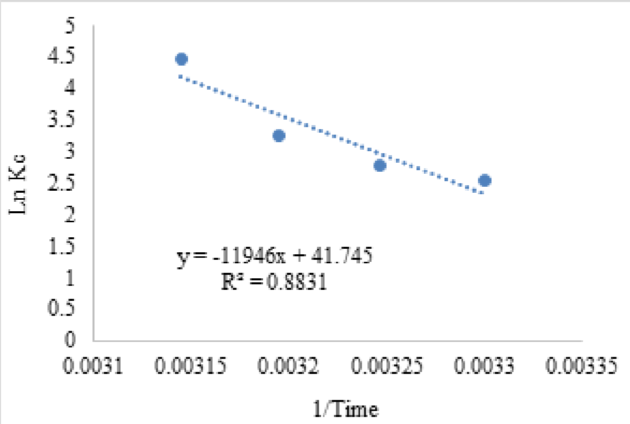

Figure 12: Vanthoff's thermodynamic studies.

present investigation's batch adsorption experiments were created using a separate BBD matrix [20-28]. Three independent variables, solution pH, catalyst dosage and agitation time, were selected for the present study in order to get the highest degradation percentage of malathion, as these three parameters control the reaction rate, shown in table 3.

Using the BBD matrix as a foundation, 17 experimental runs comprising 4 axial, 8 factorial and 5 times repetition of the center points at three different levels (-1, 0, 1) of independent parameters were produced shown in table 4. The malathion

Table 3: Different process variables in coded and un-coded form for % degradation of malathion using Fe_3O_4/marine algae NP catalyst.

Variable	Name	Range and Levels		
		-1	0	1
X1	pH of aqueous solution	6	7	8
X2	Dosage, g/L	0.08	0.1	0.12
X3	Agitation Time, T, Min	25	30	35

degradation efficiency (% Y) is the desired outcome (dependent variable). The experimental data obtained is very much close to the BBD data obtained. The difference between the observed and predicted values from the regression is termed as residual. The actual and predicted graph along with 3-D graphs are obtained in figure 14 and figure 15.

The following equation represents multiple regression analysis of the experimental data for the degradation of malathion is obtained from table 5:

Y = 82.43 + 0.2663X1 + 0.2625X2 + 0.0862X3 - 7.37X12 - 4.15X22 - 4.55X32 - 0.4675X1X2 - 0.1800X1X3 - 0.3175X2X3

Conclusion

The present study investigated the degradation of malathion by Fe_3O_4/marine algae NP. The sludge obtained by EC process for the removal of phosphate by iron plate electrodes has been filtered and calcinated, with optimum conditions, then Fe_3O_4 is synthesized with marine algae for 5 hours at room temperature and dried powder is stored. This catalyst is used for the degradation of malathion at optimum conditions, where the degradation percentage is 98.95% for 10 ppm at 318 K. The maximum degradation capacity of the catalyst is 598.2 mg/g. The cost of electrodes and marine algae is less and readily available in nature. Marine algae can be again discard-

Table 4: Results from BBD for malathion degradation by Fe_3O_4/marine algae NP catalyst.

Run no.	X1, pH	X2, Time	X3, Dosage	% degradation of malathion	
				Experimental	Predicted
1	7	25	0.08	72.48	73.07
2	8	25	0.1	72.28	71.38
3	7	30	0.1	82.48	82.43
4	6	35	0.1	70.48	71.38
5	6	30	0.12	70.82	70.51
6	8	35	0.1	68.65	70.97
7	7	35	0.08	76.86	74.23
8	7	35	0.12	74.35	73.76
9	7	30	0.1	82.38	82.43
10	6	25	0.1	72.24	69.92
11	8	30	0.12	72.42	70.68
12	8	30	0.08	70.56	70.87
13	7	30	0.1	82.4	82.43
14	6	30	0.08	68.24	69.98
15	7	30	0.1	82.42	82.43
16	7	30	0.1	82.46	82.43
17	7	25	0.12	71.24	73.87

Table 5: ANOVA for malathion degradation by Fe_3O_4/marine algae NP catalyst using BBD.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	432.06	9	48.01	10.12	0.003	Significant
pH (X1)	0.5671	1	0.5671	0.1196	0.7397	
Contact time (X2)	0.5513	1	0.5513	0.1162	0.7432	
Dosage (X3)	0.0595	1	0.0595	0.0125	0.914	
X1X2	0.8742	1	0.8742	0.1843	0.6806	
X1X3	0.1296	1	0.1296	0.0273	0.8734	
X2X3	0.4032	1	0.4032	0.085	0.7791	
$X1^2$	228.64	1	228.64	48.2	0.0002	
$X2^2$	72.39	1	72.39	15.26	0.0058	
$X3^2$	87.13	1	87.13	18.37	0.0036	
Residual	33.2	7	4.74			
Lack of Fit	33.2	3	11.07	6433.49	<0.0001	Significant
Pure Error	0.0069	4	0.0017			
Cor Total	465.27	16				

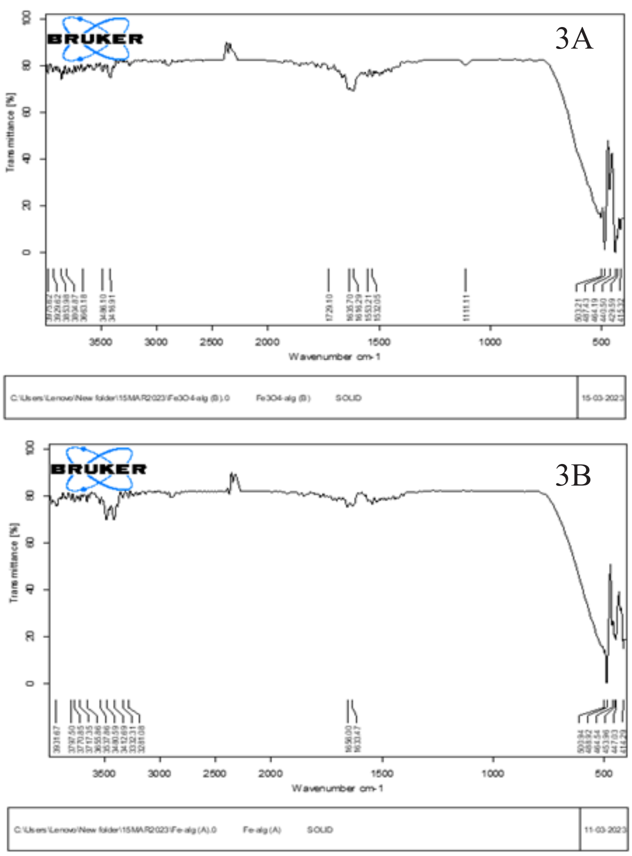

Figure 13: FTIR Spectrum of Fe_3O_4/marine algae **(a)** before degradation **(b)** after degradation.

ed into water bodies without harm to the aquatic life. A novel approach has been done for the valorization of EC sludge and degradation of malathion using Fe_3O_4/marine algae NP catalyst.

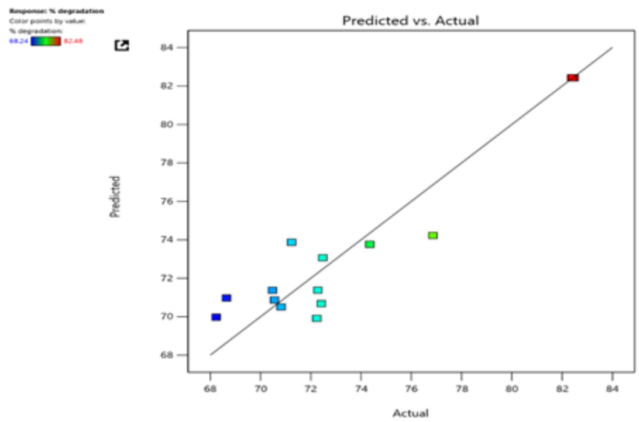

Figure 14: Graph for predicted vs experimental data.

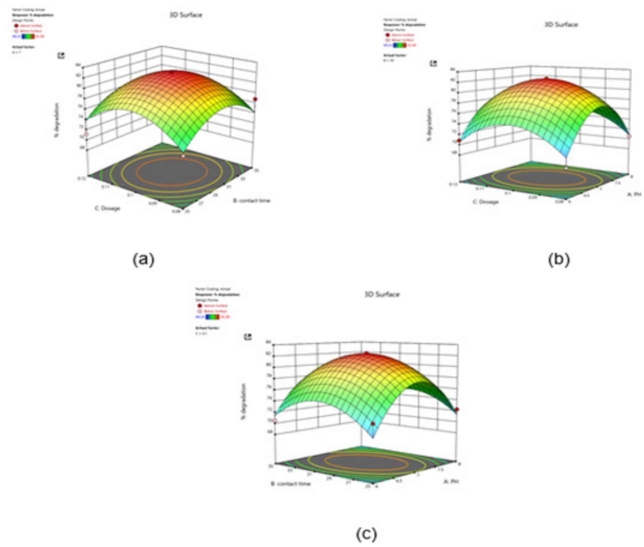

Figure 15: 3D response surface graphs for the interactive effects of **(a)** dosage and contact time, **(b)** pH and dosage, and **(c)** pH and contact time.

Conflict of Interest

On behalf of all authors, the corresponding authors states that there is no conflict of interest.

References

1. Ebba M, Asaithambi P, Alemayehu E. 2022. Development of electrocoagulation process for wastewater treatment: Optimization by response surface methodology. *Heliyon* 8(5): e09383. https://doi.org/10.1016/j.heliyon.2022.e09383
2. Shirkoohi MG, Tyagi RD, Vanrolleghem PA, Drogui P. 2022. A comparison of artificial intelligence models for predicting phosphate removal efficiency from wastewater using the electrocoagulation process. *Digital Chem Eng* 4: 100043. https://doi.org/10.1016/j.dche.2022.100043
3. Franco D, Lee J, Arbelaez S, Cohen N, Kim JY. 2017. Removal of phosphate from surface and wastewater via electrocoagulation. *Ecol Eng* 108: 589-596. https://doi.org/10.1016/j.ecoleng.2017.07.031
4. Rajaniemi K, Hu T, Nurmesniemi ET, Tuomikoski S, Lassi U. 2021. Phosphate and ammonium removal from water through electrochemical and chemical precipitation of struvite. *Processes* 9(1): 150. https://doi.org/10.3390/pr9010150
5. Nariyan E, Aghababaei A, Sillanpää M. 2017. Removal of pharmaceutical from water with an electrocoagulation process; effect of various parameters and studies of isotherm and kinetic. *Sep Purif Technol* 188: 266-281. https://doi.org/10.1016/j.seppur.2017.07.031
6. Wei V, Elektorowicz M, Oleszkiewicz JA. 2011. Influence of electric current on bacterial viability in wastewater treatment. *Water Res* 45(16): 5058-5062. https://doi.org/10.1016/j.watres.2011.07.011
7. Mansoorian HJ, Mahvi AH, Jafari AJ. 2014. Removal of lead and zinc from battery industry wastewater using electrocoagulation process: influence of direct and alternating current by using iron and stainless steel rod electrodes. *Sep Purif Technol* 135: 165-175. https://doi.org/10.1016/j.seppur.2014.08.012
8. Vasudevan S, Lakshmi J, Sozhan G. 2013. Electrochemically assisted coagulation for the removal of boron from water using zinc anode. *Desalination* 310: 122-129. https://doi.org/10.1016/j.desal.2012.01.016
9. Sharma P, Joshi H. 2016. Utilization of electrocoagulation-treated spent wash sludge in making building blocks. *Int J Environ Sci Technol* 13: 349-358. https://doi.org/10.1007/s13762-015-0845-7
10. Un UT, Onpeker SE, Ozel E. 2017. The treatment of chromium containing wastewater using electrocoagulation and the production of ceramic pigments from the resulting sludge. *J Environ Manage* 200: 196-203. https://doi.org/10.1016/j.jenvman.2017.05.075
11. Golder AK, Samanta AN, Ray S. 2006. Anionic reactive dye removal from aqueous solution using a new adsorbent—sludge generated in removal of heavy metal by electrocoagulation. *Chem Eng J* 122(1-2): 107-115. https://doi.org/10.1016/j.cej.2006.06.003
12. Ilhan F, Kurt U, Apaydin O, Gonullu MT. Treatment of leachate by electrocoagulation using aluminum and iron electrodes. *J Hazard Mater* 154(1-3): 381-389. https://doi.org/10.1016/j.jhazmat.2007.10.035
13. Shin HS, Lee JK. 2006. Performance evaluation of electrocoagulation and electrode watering system for reduction of water content in sewage sludge. *Korean J Chem Eng* 23: 188-193. https://doi.org/10.1007/BF02705714
14. Mollah MY, Schennach R, Parga JR, Cocke DL. 2001. Electrocoagulation (EC) - science and applications. *J Hazard Mater* 84(1): 29-41. https://doi.org/10.1016/S0304-3894(01)00176-5
15. Pandey N, Thakur C. 2020. Study on treatment of paper mill wastewater by electrocoagulation and its sludge analysis. *Chem Data Collect* 27: 100390. https://doi.org/10.1016/j.cdc.2020.100390
16. Umai D, Thiruchelvi R. 2019. Synthesis of nanoparticles using algae and its application in dye degradation - a review. *Int J Res Anal Rev* 6(1): 252-256.
17. Parveen K, Banse V, Ledwani L. 2016. Green synthesis of nanoparticles: their advantages and disadvantages. *AIP Conf Proc* 1724(1): 020048. https://doi.org/10.1063/1.4945168
18. Makarov VV, Love AJ, Sinitsyna OV, Makarova SS, Yaminsky IV, et al. 2014. "Green" nanotechnologies: synthesis of metal nanoparticles using plants. *Acta Naturae* 6(20): 35-44.
19. Vijayaraghavan K, Mahadevan A, Sathishkumar M, Pavagadhi S, Balasubramanian R. 2011. Biosynthesis of Au (0) from Au (III) via biosorption and bioreduction using brown marine alga *Turbinaria conoides*. *Chem Eng J* 167(1): 223-277. https://doi.org/10.1016/j.cej.2010.12.027
20. Hosseini M, Kamani H, Esrafili A, Badi MY, Gholami M. 2019. Removal of malathion by sodium alginate/biosilicate/magnetite nanocomposite as a novel adsorbent: kinetics, isotherms, and thermodynamic study. *Health Scope* 8(4): e88454. https://dx.doi.org/10.5812/jhealthscope.88454
21. Sowjanya B, Sirisha U, Juttuka AS, Matla S, King P, et al. 2022. Synthesis and characterization of zinc oxide nanoparticles: it's application for the removal of alizarin red S dye. *Mater Today Proc* 62: 3968-3972. https://doi.org/10.1016/j.matpr.2022.04.576
22. Sirisha U, Sowjanya B, Anjum HR, Punugoti T, Mohamed A, et al. 2022. Synthesized TiO_2 nanoparticles for the application of photocatalytic degradation of synthetic toxic dye acridine orange. *Mater Today Proc* 62: 3444-3449. https://doi.org/10.1016/j.matpr.2022.04.278
23. Eskandarimakvand M, Sabzalipour S, Cheraghi M, Orak N. 2022. Evaluation of efficiency of iron oxide nanoparticles (Fe_3O_4@CNT) in removal of malathion in aqueous medium using Response Surface Methodology (RSM). *Pollution* 8(1): 281-293. https://doi.org/10.22059/poll.2021.323942.1090
24. Mareedu T, Poiba V, Vangalapati M. 2021. Green synthesis of iron nanoparticles by green tea and black tea leaves extract. *Mater Today Proc* 42: 1498-1501. https://doi.org/10.1016/j.matpr.2021.01.444
25. Surendra B, Raju BM, Onesimus KNS, Choudhary GL, Paul PF, et al. 2020. Synthesis and characterization of Ni doped TiO_2 nanoparticles and its application for the degradation of malathion. *Mater Today Proc* 26: 1091-1095. https://doi.org/10.1016/j.matpr.2020.02.216
26. Gowthami V, Sowjanya B, Kumar MN, Vangalapati M. 2023. Synthesized MgO/Chitosan nanocomposite: it's application for the removal of Dicofol and Optimization by Box Benhken design. *Nanoworld J* 2023 9(1): 1-7.https://doi.org/10.17756/nwj.2023-110
27. Poiba VR, Sowjanya B, King P, Vangalapati M. 2023. Removal of methylene blue dye by using synthesised *Grevillea robusta* silver nanoparticles and optimisation of experimental parameters by response surface methodology (central composite design). *Adv Mater Process Technol* 1-5. https://doi.org/10.1080/2374068X.2023.2192393
28. Myneni VR, Kanidarapu NR, Shaik F, Vangalapati M. 2022. Response surface modeling of the removal of methyl orange dye from an aqueous solution using magnesium oxide nanoparticles immobilized on chitosan. *Iranian J Chem Chem Eng* 41(5): 1602-1618. https://doi.org/10.30492/ijcce.2021.122511.4002