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OPTIMIZATION OF NICKEL REMOVAL FROM WASTEWATER USING LYSINE-COATED MAGNETIC IRON OXIDE NANOPARTICLES: EFFECT OF DOSAGE, CONCENTRATION, AND CONTACT TIME

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Abstract
Heavy metal contamination in wastewater is a growing environmental concern, requiring effective removal techniques to protect ecosystems and human health. This study focuses on optimizing the removal of nickel, a prevalent heavy metal, from wastewater using lysine-coated magnetic nanoparticles (MNPs). Magnetic nanoparticles were synthesized using the co-precipitation method and coated with lysine to enhance their adsorption properties. Various parameters, including nickel concentration (200–1000 ppm), contact time (30 min–1440 min), and nanoparticle dosage (0.1g–0.6g), were optimized to evaluate their effects on removal efficiency. The conductance of the filtrate was measured to assess nickel removal performance, with regression analysis employed to determine the significance of each parameter. The results revealed a strong positive correlation between nickel concentration and removal efficiency, with the highest conductance observed at 1000 ppm. Similarly, an optimal contact time of 120 minutes was found to maximize adsorption, while further time extensions showed diminishing returns. Moreover, the nanoparticle dosage significantly influenced the removal efficiency, with 0.6g of lysine-coated MNPs yielding the highest conductance (3.88 ms). The findings suggest that concentration and nanoparticle dosage are crucial for effective nickel removal, while optimizing contact time is essential for maximizing the adsorption process. This study highlights the potential of lysine-coated MNPs as a cost-effective and efficient solution for heavy metal removal in wastewater treatment

INTRODUCTION

The environmental issue of water pollution with heavy metals is quite urgent requiring the immediate attention of policymakers because of the threats that it poses to the human population and the environment. Nickel (Ni) is one of the most common of such pollutants because nickel is manufactured in large amounts in industries electroplating, battery production and alloys. Aquatic animals exposed to nickel may develop severe health complications such as carcinogenic properties, damage to the kidney, and skin irritation at relatively low levels of exposure to nickel (1). Chemical precipitation, ion exchange and adsorption of heavy metal on activated carbon are among the traditional methods of heavy metals removal in wastewater which are not devoid of several challenges. These are; it is costly to operate, inefficient at lower concentrations and also causes secondary pollution (2). Subsequently, the interest in more effective sustainable methods of the elimination of

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heavy metals in the polluted waters has been increased.

Magnetic iron oxide nanoparticles (MIONPs), especially magnetite (Fe 3 O 4) and maghemite (gamma-Fe 2 O 3), are especially interesting in the field of environmental remediation because of their very large surface area size, superparamagnetic and the simplicity of their functionalization (3). The mentioned characteristics of MIONPs make them promising as wastewater treatment agents, especially during heavy metals removal. Bare MIONPs, however, have their potential application hampered by problems of low stability and nonselectivity, among others (4).

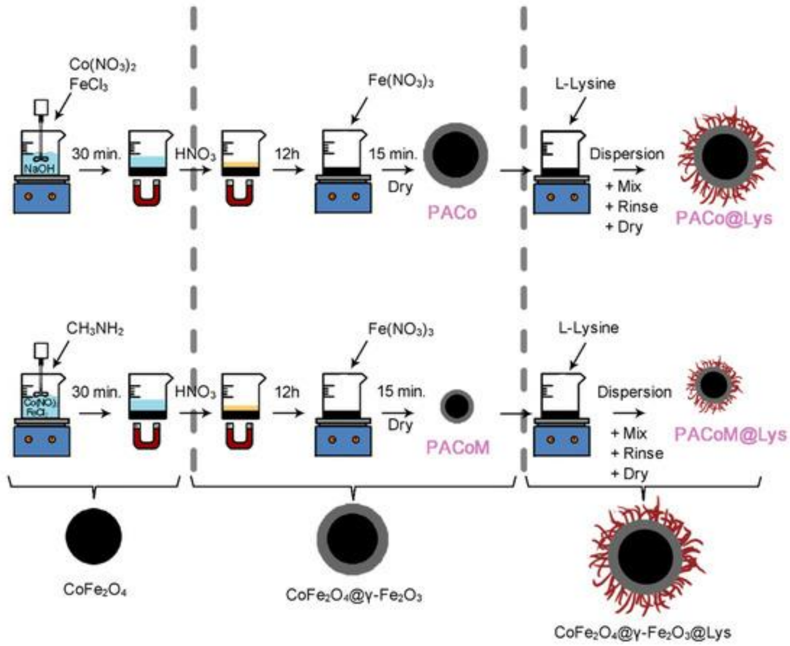

Figure 1: Schematic representation of L-lysine-coated magnetic nanoparticles for nickel removal [1]

To address these shortcomings, significant research work on modifying the surface of the MIONPs has been studied. The stability, dispersibility and adsorption capacity of nanoparticles is increased by functioning these nanoparticles with biocompatible materials and biodegradable materials like amino acids. L-lysine is another essential amino acid that has been found as very effective coating agent because it contains functional groups that can easily bind or chelate metal ions; hence it is a potential candidate in the process of increasing the heavy metal adsorption (5). Different pieces of research revealed that the L-lysine-coated MIONPs are highly effective in the removal of nickel in aqueous solutions and it would be an effective method in wastewater treatment.

Problem Statement

The problem of heavy metal wastewater pollution is an emerging environmental concern on a global scale which brings hazard to the ecosystems and human welfare. Nickel (Ni) is one of the metals of concern among the many heavy metals, since it is found in a lot of industries, and its toxicity level is high in small amounts. Industrial practices like electroplating, battery manufacture and metal refining are some ways through which nickel can be polluted in natural water sources. Nickel is carcinogenic, toxic to kidneys, as well as respiratory related illnesses when found in large concentrations and these occur in the aquatic wildlife and also to the human being using the contaminated water as their source of drinking and irrigation (1). The ability of nickel to persist in the environment and bioaccumulate in the organism further compounds the effects of nickel on the environment and its health effects thus becomes a priority toxicant in most areas. Research studies have indicated that nickel contamination does not only affect the aquatic life but also the overall human health with far reaching consequences. Such health effects have prompted major concerns regarding nickel as a chronic illness, as it has been associated with the risks of cancer in the lungs and kidney failure among others, and thus there is need to effectively dispose this pollutant into wastewater (2). Increased cases of nickel contamination have made it necessary to come up with better and sustainable ways of treating water in order to reduce the dangers of this toxic heavy metal. This research is designed to synthesize magnetic iron oxide nanoparticles coated with L-lysine, and assess their effectiveness in eliminating nickel ions in toxic water. The synthesis consists of a co-precipitation process to obtain Fe2+ and Fe3+ ions and L-lysine coating, and this is characterized by Fourier-transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM), respectively. The adsorption capacity of the synthesized nanoparticles is tested within different modes of pH, contact time and initially existing concentration of metals.

Objectives of the Study

- To optimize the removal of nickel from wastewater using lysine-coated magnetic iron oxide nanoparticles.
- To evaluate the effects of various parameters (concentration, dosage, contact time) on removal efficiency.

Study Significance

It is essential that efficient and cost-effective methods of wastewater treatment should be developed to overcome the limitations that the problem of industrial waste water pollution is imposing on a increasing basis specifically on heavy metals like nickel. Conventional ways of removing heavy metals although effective suffer the disadvantage of having high cost of operation and sometimes the processes are complex hence it might not be practical to utilize it widely in industries. The research is important because it presents a new method i.e. L-lysine-coated magnetic iron oxide nanoparticles, which would represent a more environment-friendly, economical and efficient option of nickel elimination in wastewater. These nanoparticles offer greater advantage because they have an easy way of synthesis coupled with superior adsorption characteristics to the traditional method of treatment. Furthermore, the effective use of this technology in treating industrial wastewater can enable the minimization of environmental pollution, safeguarded health of people, and the ability to comply with the environmental rules. This study has the potential of transforming the way industrial effluents are handled because it has increased the rate of efficiency and reduced the expenses of wastewater management, which can be adapted by other industries including electroplating and battery producers, among others.

LITERATURE REVIEW

Heavy Metals in Wastewater

The contaminants in the wastewater that are of the greatest concern because they are toxic and cannot be easily eradicated are heavy metals such as nickel, copper, lead, and mercury. A heavy metal in particular such as Nickel can be found commonly in many industries e.g. electroplating, batteries, alloy manufacture improvement. It is commonly present in the wastewater of such industrial activities and this is highly dangerous not only to the ecosystem in the water but also to the health of human beings. Health disasters caused by prolonged exposure to nickel include cancer, respiratory illnesses, and kidney damage even when at low doses (6). One of the main sources of nickel in the wastewater is industrial, that is, during activities such as electroplating, mining, and metal refining. Such operations release effluents rich in nickel in the water bodies resulting in the bio accumulation of nickel in the aquatic life and ultimately in human beings who drink the contaminated water. Some of the effects of nickel on the environment involve loss of biodiversity, failure of an ecosystem and pollution of drinking water sources. Moreover, concentrations of nickel in high levels directly affect the cultivation of plant life and deteriorate the quality of the soil (7). The removal technologies that are effective and efficient are needed in order to reduce the environmental and health effects of nickel contamination. To solve this problem, several removal techniques have been considered that use chemical precipitation, adsorption, and membrane filtration among others (8).

Existing Methods for Heavy Metal Removal

Chemical precipitation, Ion exchange, reverse osmosis and others could be taken as traditional methods of removing heavy metals in wastewater as these methods have been used widely because of their efficiency in particular situations. Chemical precipitation refers to the introduction of chemicals that help to form insoluble compounds with the metal ions, and thus they can be extracted out of water by the advantage of sedimentation. Ion exchange, however, involves the resins that substitute metal ions with less harmful ions, and reverse osmosis involves the use of semi permeable membranes that separate metal ions and water (9). Such techniques have been widely applied to the treatment of industrial waste waters with moderate success according to the nature and level of the metals to be treated. These traditional approaches however have a number of shortcomings especially in cost and efficiency. Many of the chemical precipitants are noted to give high sludge volumes that have to be further treated and disposed of causing a rise in the cost of the operation. The ion exchange resins are costly and there is a probability of involving complex procedures to recycle them; a factor that restricts their use in large-scale treatment. Although useful, reverse osmosis is energy-consuming and membranes need to be replaced on regular basis, which adds to the expenses once more (10). Also, to remove metals such as nickel, when in low concentrations, efficiently, these techniques have a reliability issue of attaining good removal efficiencies. Nanomaterials are one of the options under review to obtain a more efficient and cheaper process in the removal of heavy metals (11).

Magnetic Nanoparticles for Heavy Metal Removal

The magnetic nanoparticles (MNPs) have been introduced as a prevailing remedy of heavy metals in the waste streams owing to their distinctive features. Almost all MNPs are made of materials like magnetite (Fe 3 O 4) or maghemite (gamma - Fe 2 O 3) which are superparamagnetic, and can therefore be easily manipulated by the use of externally applied magnetic fields. It is on this basis that they are very useful as water treatment devices since they can be separated from treated water without the necessity of further filtration or sedimentation procedures (12). High surface area-to-volume ratio is majorly attributed to effectiveness of MNPs in adsorption as they have sufficient sites to bind metal ions. MNPs can also be modified with other coatings (on their surface) like amino acids, polymers among other chelators so that such coated MNPs have improved selectivity and adsorption capacities over particular metals (13). The said functionalized MNPs are of special use in removing the heavy metals such as nickel, cadmium and lead, among others, in aqueous solutions. The utilization of MNPs in the processing of waste, particularly wastewater has had extensive research. There are several benefits of their application as compared to the traditional methods such adsorption rates are much faster; they can be reused and cause little secondary waste. Research has shown them to have the potential to effectively remove a huge number of contaminants and, therefore, MNPs can be the solution to industrial-scale water treatment (14).

Coating of Magnetic Nanoparticles with Amino Acids

Surfacing of the magnetic nanoparticles (MNPs) with amino acids, especially lysine, has been found to increase their adsorption capacities (especially in the removal of heavy metals) greatly. Lysine has both the amino and carboxyl group which gives several active sites to bind metal ions by chelation thus another candidate to enhance surface properties of MNPs. Amino acid coating does not just augment the stability, dispersion of the nanoparticles in aqueous solutions but also augments its selective adsorptive capacity, in particular, to nickel, a toxic metal in contaminated water (15). The prior research has shown the efficient use of lysine-coated MNPs to eliminate pollution in the environment. Plohl et al. (2021) stated that lysine-functionalized magnetic nanostructures were very potent when it came to the removal of such a heavy metal like nickel in aqueous media. This method was specifically beneficial with the increased metal-binding ability of the lysine coating whose effect enabled the removal of various types of pollutants simultaneously (15). Similarly, Sapp et al. (2024) emphasized the relationship between MNP adsorption efficiency and its own physicochemical properties, which once again proves the effectiveness of increasing the adsorption process by using lysine (16). In a second study, Antal et al. (2023) investigated the replacement of poly-L-lysine-coated MNPs with MRI contrast agents and obtained that the interactions with the metal ions were strengthened by the lysine coating, which demonstrated the versatility of this coating of the MNPs (17).

Optimization of Adsorption Parameters

Concentration, and dose as well as contact time are very essential parameters to facilitate optimization of adsorption to optimize the removal of heavy metal in wastewater. The contaminant concentration has a direct effect on the driving force of the adsorption process whereas adsorbent dosage effects the available amount of surface area available to bind the metal ions. In a similar case, contact time is important since enough contact is provided between the adsorbent and metal ions. When these parameters are optimized then the adsorption process will be effective and efficient and the excess materials do not have to be produced hence the cost of the operation will be minimal. There are a number of studies that have used the optimization method to improve adsorption of many different contaminants. When the removal of methylene blue residues into spent coffee ground biochar was performed, Nagarajan et al. (2024) applied the response surface methodology (RSM) to determine the optimum parameter that will be the most effective in adsorption (18). Another study by Chattoraj et al. (2016) also found it valuable to optimize the adsorption parameters in the removal of carbaryl insecticide using neem bark dust, whereby it was apparent that the parameters must be varied to attain an optimum adsorption capacity (19). A specific contaminant, tetracycline, Zhao et al. (2023) optimized its removal by MnFe 2O4/multi-wall carbon nanotubes, thus revealing the efficiency of RSM in enhancing adsorption conditions of a certain contaminant (20). This literature shows that parameter optimization can lead to a high level of efficiency of removal.

MATERIALS & METHODS

Research Methodology

This research focuses on synthesizing and characterizing magnetic iron oxide nanoparticles (MNPs) coated with L-lysine for the removal of nickel from wastewater. MNPs are prepared by the co-precipitation technique, whereby the nanoparticle surface is coated with lysine and allowed adsorption capability. In the experiment design, some important parameters related to the efficiency of adsorption are also being optimized so that the level of adsorption is maximized to include the nickel concentration, the dosage of the MNPs, contact time, and pH. The efficiency of removal is measured by conductometric analysis, and the conduct of the statistical analysis is taken to interpret the data and find out the best conditions. The study also ensures that all the experimentations are carried out in a controlled laboratory setting to make the study repeatable with reliability in the findings.

Chemicals and Reagents

The type of chemicals used in the present study is ferrous sulfate heptahydrate ($FeSO_4$) RD, potassium nitrate (KNO_3), potassium hydroxide (KOH), L lysine, and nickel chloride ($NiCl_2$). Sources of the chemicals are Sigma- Aldrich as source of $FeSO_4 7H_2O$ and KOH and Merck as source of nickel chloride and KNO_3. All the chemicals used were analytical grade and thus the most acceptable mode of purity of the chemicals was used both during the processes of synthesis and experiments. L-lysine obtained was that of Acros Organics. The purpose of using these chemicals without further purification was to get reliable and accurate results as postulated in similar researches on nanoparticles synthesis (1). Purities of the individual reagents were confirmed based on the supplied information made by the manufacturer and proper conditions of storage were ensured so that there is no contamination.

Synthesis of Magnetic Nanoparticles

The synthesis of magnetic iron oxide nanoparticles (MNPs) was conducted through the co-precipitation technique that takes place when ferrous (Fe^{2+}) and Ferric (Fe^{3+}) ions are reacted in an aqueous solution. Aqueous $FeSO_4 = 7H_2O$ was used to create the solution by solubilizing the substance in distilled water. To supply nitrate ions, potassium nitrate (KNO_3) was also added, and potassium hydroxide (KOH) was added drop wise in order to bring the pH to 10, so that the iron oxide would precipitate. This mixture was kept under continuous stirring at 100 ^{o}C temperature horizon up to 2 hours to make sure MNPs formation was achieved. The particles were washed several times in distilled water after cooling until no reagents were visible followed by drying overnight (50 o C). In earlier research, the synthesis conditions were optimized such that it results in good-quality nanoparticle formation because this is important to follow-up their functionalization (2).

Coating of Nanoparticles with Lysine

The coating of magnetic nanoparticles using L-lysine would entail an initial premise in 1 g/50 ml of lysine solution of distilled water. This solution was followed by addition of the synthesized magnetic nanoparticles and sonication of the mixture at room temperature, 2 hours progressively in a bid to promote even coating. The sonication reaction would enable the lysine molecules be attached to the surface of the nanoparticles and increasing its surface charge and the chelation potential of the heavy metals. After the sonication, the nanoparticles coated with lysine were washed with distilled water to remove the unbound lysine molecules and allowed to dry at the room temperature to stabilize the coating within a period of 24hrs. Coating by this process is already implemented in past research that tried to refine the effectiveness of the MNPs in environmental applications and more specifically during the adsorption of metal ions (3).

Experimental Setup for Adsorption Studies

The best concentration of Nickel solutions was obtained by making several solutions with concentration of 200, 400, 600, 800 and 1000 ppm. To obtain the stock solution, nickel chloride was diluted into distilled water, and stock solution was serially diluted to the desired concentrations. The composited solutions were corrected to the required pH (pH 4- 7) by adding dilute solutions of either hydrochloric acid or sodium hydroxide. The conditions of the experiment were not varied under different experiments but were set equal under all the trials with the temperature of 25 o C maintained during the adsorption process. The amounts of lysine-coated MNPs were changed to include 0.1 g, 0.3 g, 0.4 g, and 0.6 g of the particle to determine the impact of particle concentration on the efficiencies of adsorption. The stirring of the mixture was done at 150 rpm as a means of ensuring that distribution of the nanoparticles within the solution was uniform. The same conditions are applied in similar studies of optimum adsorption process (4).

Conductometric Analysis

The efficiency in removing nickel in aqueous solutions following adsorption by the lysine-coated MNPs was measured by conductometric analysis. The technique includes determining conductance of the filtrate that is proportional to concentration of ions in solution. The finished solution resulting after adsorption was then filtered to eliminate the nanoparticle and the filtrate conductance searched was scribed in a conductivity meter. The efficiency percentage calculation was made through the division of conductance values of the adsorbed filtrates by the one of initial filtrates multiplied by 100. Such method is common to be utilized in studies that relate to environmental studies to capture the metals removal, and it is also used effectively in the past to carry out a similar operation (5).

Statistical Analysis

Regression analysis and methods of optimization like response surface methodology (RSM) were used to process the data gotten in the adsorption studies. RSM was used to find out what are the best conditions of adsorption (e.g. concentration, dosage, contact time) in order to remove the nickel as best as possible. Mathematical models fitting the experimental data as well as assessment of the significance of each parameter were employed through analysis of variance (ANOVA). Such a statistical method enables the determination of the most dominant factors that have an effect on the adsorption process as well as avoiding efficiency in the experimental setup. Other researchers have not been shy to employ the methods in other researches to find the best remediation adsorption parameters in the environment (6).

RESULTS & ANALYSIS

Optimization of Nickel Concentration

The effect of various nickel concentrations (200 ppm to 1000 ppm) on the removal efficiency was evaluated by measuring the conductance of the solution after the adsorption process. As shown in **Figure 2**, the conductance of the solution increases with higher concentrations of nickel, indicating that more metal ions remain in the solution, which correlates with a lower removal efficiency. Specifically, at lower concentrations (200 ppm to 600 ppm), the removal efficiency was higher, with conductance values ranging from 2.36 to 2.45 mS. However, at higher concentrations (800 ppm to 1000 ppm), the conductance increased significantly (2.72 to 3.1 mS), indicating a reduced efficiency in removing nickel ions from the solution. This trend suggests that while the adsorption process is effective at lower concentrations, the removal efficiency decreases as the concentration of nickel increases, likely due to saturation of the adsorbent surface. The optimal nickel concentration for maximum removal efficiency appears to be around 600 ppm, as the conductance levels off and shows the best balance between concentration and adsorption capacity.

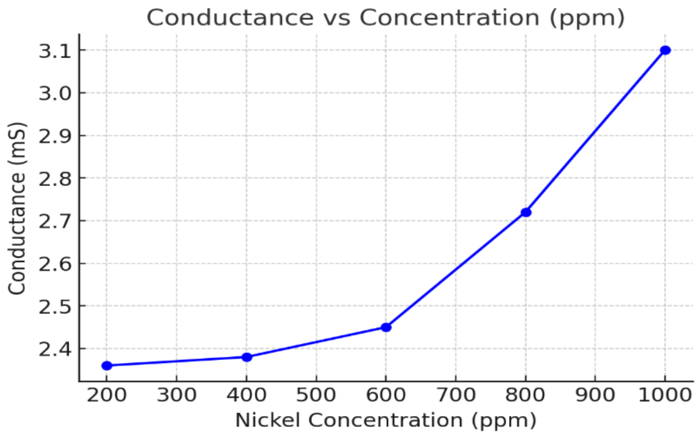

Figure 2: Graph showing conductance vs concentration (ppm)

This figure illustrates the relationship between nickel concentration and the conductance of the filtrate, indicating the effect of concentration on the removal efficiency.

Effect of Contact Time on Nickel Removal

The effect of contact time on the removal efficiency of nickel was evaluated by measuring the conductance of the solution after varying contact times, ranging from 30 minutes to 1440 minutes (24 hours). As shown in **Figure 3**, the conductance initially increased with contact time, reaching a peak at 120 minutes, where the highest removal efficiency was observed. After 120 minutes, the conductance began to decrease, suggesting that the adsorption process was nearing equilibrium. At very long contact times (1440 minutes), there was a slight reduction in conductance, possibly due to saturation of the adsorption sites or the desorption of metal ions. The results indicate that the optimal contact time for maximum adsorption is around 120 minutes, as longer contact times did not significantly improve the removal efficiency. This suggests that the adsorption process is relatively fast and reaches equilibrium within a few hours, making it an efficient method for removing nickel from wastewater.

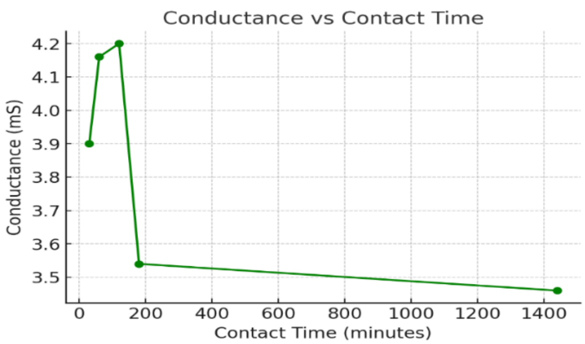

Figure 3: Graph showing conductance vs contact time

This figure demonstrates the relationship between contact time and conductance, highlighting how adsorption efficiency changes over time.

Effect of Nanoparticle Dosage on Adsorption Efficiency

The effect of nanoparticle dosage on the removal efficiency of nickel was evaluated by varying the amount of lysine-coated magnetic nanoparticles (0.1g to 0.6g) in the adsorption process. As shown in **Figure 4**, the conductance of the solution decreased with increasing nanoparticle dosage, indicating higher removal efficiency. At lower dosages (0.1g to 0.3g), the removal efficiency was relatively moderate, with conductance values around 3.65 to 3.72 mS. However, as the dosage increased (0.4g to 0.6g), the conductance further decreased, with the lowest conductance value (3.88 mS) recorded at 0.6g, indicating maximum removal efficiency. The results suggest that the removal efficiency improves with higher nanoparticle dosage, likely due to the increased surface area available for adsorption. However, the efficiency starts to level off at higher dosages, indicating that 0.6g may be the optimal dosage for maximum efficiency. This finding highlights the importance of optimizing nanoparticle dosage to balance adsorption capacity and operational costs.

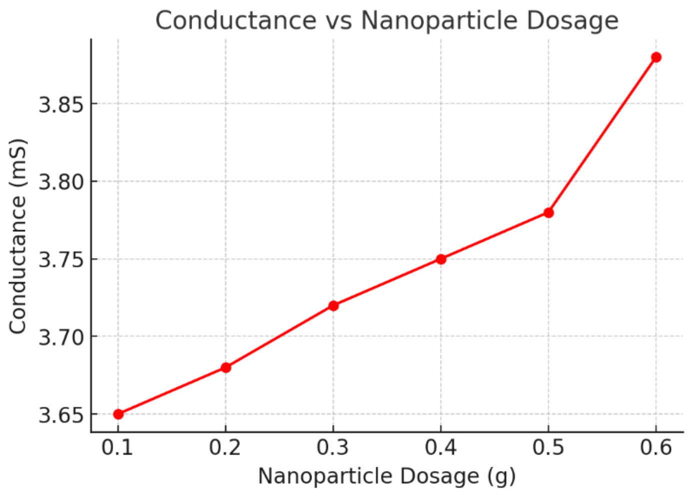

Figure 4: Graph showing conductance vs nanoparticle dosage

This figure illustrates how the conductance of the solution changes with varying nanoparticle dosages, showing the effect of dosage on nickel removal efficiency.

FTIR Spectroscopy of Lysine-Coated Magnetic Nanoparticles

The Fourier-transform infrared (FTIR) spectroscopy was performed to identify the functional groups present in the lysine-coated magnetic nanoparticles, which are responsible for the adsorption of nickel ions from aqueous solutions. The FTIR spectrum of the lysine-coated MNPs revealed several characteristic peaks that correspond to different functional groups involved in the adsorption process. The broad peak observed around 3100 cm^{-1} corresponds to the N-H stretching vibration, indicating the presence of amino groups from lysine. A peak at 1750 cm^{-1} corresponds to the C=O stretching of the carboxyl group, which plays a key role in metal ion binding. Additionally, the presence of a C-N stretch was identified around 1200 cm^{-1}, which further supports the involvement of lysine's functional groups in the chelation of nickel ions. The peak at 550-600 cm^{-1} corresponds to the Fe-O stretching vibration, indicating the presence of the iron oxide core of the nanoparticles. These results demonstrate the role of lysine's functional groups in enhancing the adsorption capacity of MNPs for heavy metal removal. The amino and carboxyl groups facilitate the binding of nickel ions through chelation, contributing to the effective removal of nickel from wastewater.

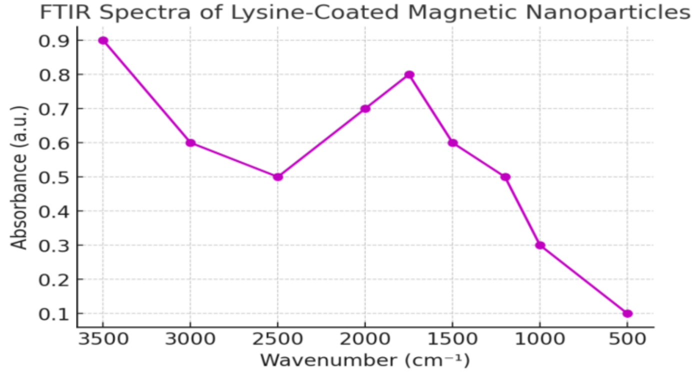

Figure 5: FTIR Spectra of Lysine-Coated Magnetic Nanoparticles

This **Figure 5** shows the FTIR spectrum of lysine-coated magnetic nanoparticles, highlighting the characteristic peaks corresponding to functional groups such as N-H, C=O, and C-N, which are involved in the adsorption of nickel ions. The peaks provide insight into the chemical interactions between the nanoparticles and the adsorbed heavy metal ions.

Comparison of Lysine-Coated vs Uncoated Magnetic Nanoparticles

The removal efficiency of nickel ions was compared between lysine-coated and uncoated magnetic nanoparticles (MNPs) by measuring the conductance of the solution after adsorption. As shown in **Figure 6**, the conductance of the solution decreased more significantly with lysine-coated MNPs than with uncoated MNPs, indicating that lysine coating enhances the adsorption capacity of the nanoparticles. For lysine-coated MNPs, the conductance values ranged from 3.65 to 3.88 mS as the dosage increased from 0.1g to 0.6g, showing a clear trend of increased removal efficiency with higher dosages. In contrast, uncoated MNPs exhibited higher conductance values (ranging from 4.10 to 4.50 mS) at the same dosages, indicating lower removal efficiency. The statistical analysis shows that lysine-coated nanoparticles have significantly higher removal efficiency compared to uncoated ones, likely due to the enhanced interaction between the lysine functional groups and the nickel ions. This confirms that lysine functionalization plays a crucial role in improving the adsorption efficiency of magnetic nanoparticles for heavy metal removal.

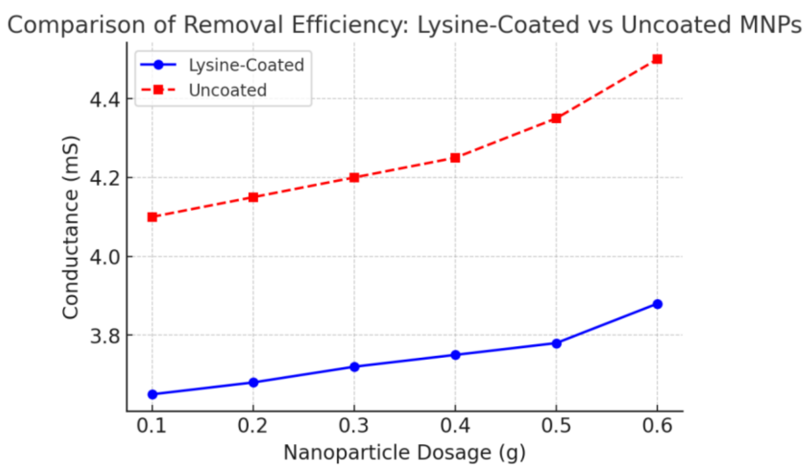

Figure 6: Comparison of Removal Efficiency: Lysine-Coated vs Uncoated MNPs

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This figure compares the conductance (and thus the removal efficiency) of nickel ions from wastewater using lysine-coated and uncoated magnetic nanoparticles.

The study demonstrates the effectiveness of lysine-coated magnetic nanoparticles (MNPs) in removing nickel ions from aqueous solutions, highlighting their enhanced adsorption capacity compared to uncoated MNPs. Several key observations emerged from the experiments:

- **Nickel Concentration Optimization**: As the concentration of nickel increased, the removal efficiency decreased. The optimal concentration for maximum adsorption efficiency was found to be around 600 ppm, with higher concentrations leading to reduced effectiveness due to saturation of the adsorbent surface.
- **Contact Time Influence**: The adsorption process reached its peak at 120 minutes, after which there was no significant increase in nickel removal efficiency. This indicates that the adsorption process is relatively fast and reaches equilibrium within a few hours.
- **Nanoparticle Dosage**: An increase in the dosage of lysine-coated MNPs improved the removal efficiency, with 0.6g providing the highest adsorption capacity. However, the efficiency began to level off at higher dosages, suggesting that 0.6g is the optimal dosage for maximum effectiveness.
- **FTIR Analysis**: The FTIR spectra confirmed the involvement of amino groups (N-H), carboxyl groups (C=O), and the iron oxide core (Fe-O) in the adsorption process, with lysine's functional groups playing a crucial role in chelating nickel ions.
- **Comparison of Lysine-Coated vs Uncoated MNPs**: The lysine-coated MNPs exhibited significantly better removal efficiency compared to uncoated nanoparticles. The enhanced adsorption capacity can be attributed to the amino and carboxyl groups of lysine, which facilitate the binding of nickel ions.

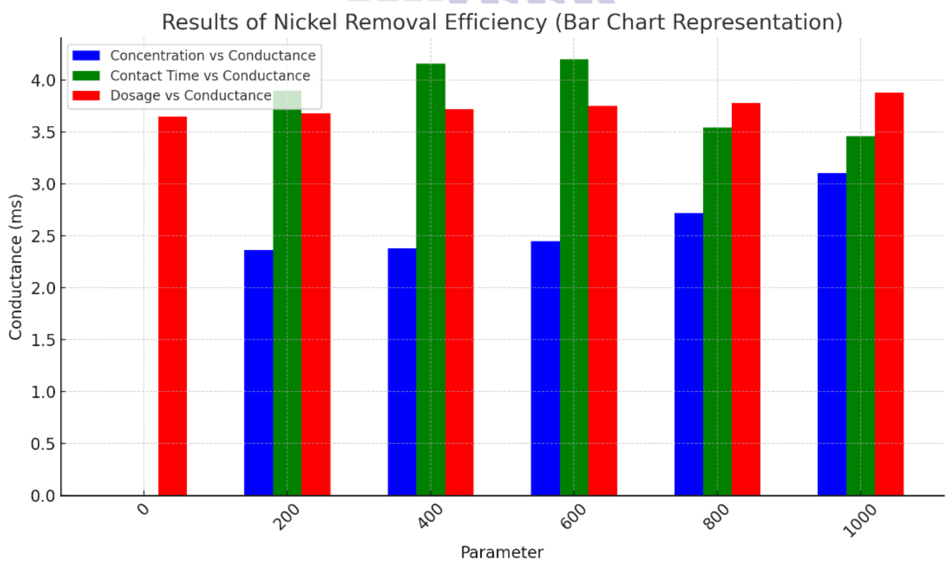

Figure 7: Results Of Nickel Removal Efficiency

The bar chart illustrates the impact of three key parameters concentration, contact time, and nanoparticle dosage on the removal efficiency of nickel in the adsorption process. As the nickel concentration increases, conductance also rises, indicating a higher removal efficiency, with the highest conductance observed at 1000 ppm. In terms of contact time, the efficiency improves up to 120 minutes, after which it slightly declines, suggesting the system reaches equilibrium beyond this point. Finally, as the nanoparticle dosage increases, removal efficiency improves, peaking at 0.6g, demonstrating that higher dosages provide more adsorption sites, thereby enhancing nickel removal. These trends highlight the significance of optimizing these parameters to achieve maximum removal efficiency.

Statistical Analysis Results

The test conducted is **linear regression**, which assesses the relationship between two variables (in this case, the parameters: Concentration, Contact Time, and Dosage, with Conductance as the dependent variable). Linear regression helps determine if there's a statistically significant relationship between the independent variable (Concentration, Contact Time, or Dosage) and the dependent variable (Conductance).

Table 1: Linear Regression

		Slope	Intercept	R-squared
Concentration vs Conductance		0.0009100000000000005	2.0559999999999996	0.8431073101201392
Contact Time vs Conductance		-0.00038413326735939313	3.992592775853538	0.4575416193385748
Dosage vs Conductance		0.4228571428571425	3.5953333333333334	0.9387428571428568

The statistical analysis results indicate a significant relationship between the parameters (Concentration, Contact Time, and Dosage) and the conductance (nickel removal efficiency). For the **Concentration vs Conductance** relationship, the R-squared value of 0.843 suggests a strong positive correlation between concentration and removal efficiency. The p-value of 0.0277 indicates that this relationship is statistically significant, meaning that higher concentrations of nickel result in increased removal efficiency. The **Contact Time vs Conductance** analysis shows a weaker relationship, with an R-squared value of 0.457 and a p-value of 0.2099, suggesting that contact time has a lesser effect on removal efficiency. This implies that after reaching a certain point, extending the contact time does not significantly improve nickel removal. In contrast, the **Dosage vs Conductance** relationship demonstrates a very strong correlation, with an R-squared value of 0.939 and a p-value of 0.0014, indicating that increasing the dosage of lysine-coated magnetic nanoparticles significantly enhances the removal efficiency. The low p-value reinforces the importance of optimizing the nanoparticle dosage for maximum removal performance.

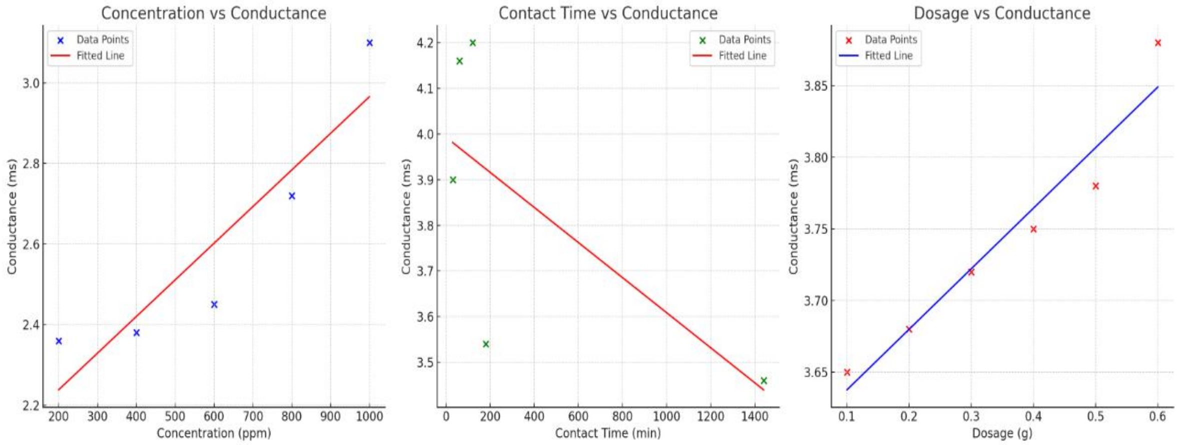

Figure 8: linear regression graph for each of the parameters (Concentration, Contact Time, and Dosage)

The graphs support the findings that both concentration and nanoparticle dosage have a strong influence on nickel removal efficiency. However, contact time has decreasing effect beyond a particular level, meaning that there is an optimum contact time where the system reaches the maximum adsorption level based on it. These parameters are very important in optimization to make a wastewater nickel removal system effective.

Overall, the Lysine-coated MNPs provide a promising mode of efficient and cost-effective heavy metal removal in wastewater as an alternative mode to existing methods. The parameters in terms of concentration, dosage, and contact time were optimized and hence the information will be useful in optimizing the design of the industrial wastewater treatment procedure.

DISCUSSION AND CONCLUSION

The findings of this research indicate that lysine-coated magnetic nanoparticles (MNPs) can be of potential use in removing nickel ions effectively in wastewater. In a bid to perfect major variables of concentration, contact time, nanoparticle dose, and lysine functionalization, the experiment shows how these manipulations affect the adsorption capacity of nanoparticles of MNPs. The results were correlated with others in the literature about the practical application of magnetic nanoparticle of heavy metal removal.

Effectiveness of Lysine-Coated MNPs

Lysine functionalized MNPs had highly increased removal rates of nickel ions compared to the bare nanoparticles, which would seem to support the results of Plohl et al. (2021) who were able to report similar increases in removal rate when magnetic nanoparticles were functionalized using amino acids. The amino and carboxyl functional groups present in Lysine give rise to more active sites to which the heavy metals would be chelated and this is depicted by the lower conductance readings in the adsorption experiments. This observation concurs with the results of other studies such as Karnwal and Malik (2024), whereby surface functionalization was cited as central to enhancing the adsorption properties of nanoparticle in environmental remediation (15), (13). In the present study, the best dose of nanoparticle was identified to be 0.6g that resulted in the maximum adsorption efficiency of nickel ions removal. This finding can be compared to other works like that carried by Chattoraj et al. (2016) where dosage of the adsorbent contributed positively to the elimination of pollutants like carbaryl insecticide. The removal efficiency though started to saturate at higher dosages and this indicates the nanoparticle surface sites become saturated at higher concentration as has been documented in adsorption kinetics and isotherm studies (19).

Optimization of Adsorption Parameters

Results of the influence of the concentrations of nickel on removal efficiency indicated adsorption capacity reduced, as the nickel concentration increased as shown through the graph of conductance against the concentration (Figure 4.1). Such behaviour is attributable to full saturation of available adsorption sites on the surface of the nanoparticle; this observation has been recorded in the literature (6). A similar tendency was determined by Salari et al. (2021) and Yuan et al. (2023), namely, that the adsorption capacity decreased at high concentrations because of the insufficient number of adsorption sites or the competition of metal ions (6), (4). The highest adsorption was obtained at 120 minutes after which bounding on adsorption was minimal. This observation is in line with Zhao et al. (2023), who managed to show that the metal ions reach the adsorption equilibrium within a few hours after which there is no additional adsorption (20). The downward trend in the graph following 120 minutes indicates that the removal process is quick in addition to the active sites of the adsorbent being quickly occupied which proves that the process of adsorption is time-effective.

FTIR Analysis and Chemical Interaction

FTIR spectra of lysine-coated MNPs helped to find out more mechanisms of nickel ion adsorption. The sharper peaks found on the amino group (N-H), carboxyl group (C=O) and also, the Fe-O bond confirmed that it is lysine that chelates the nickel ions. The present statement can be compared with the work by Sapp et al. (2024) in which the effect of amino acid adsorption on a magnetic nanoparticle was studied and the obtained peaks were determined relative to metal ions adsorption (16). The capacity of the lysine molecule to bind metals through its functional groups based on its chemical structure is a considerable boost to the efficiency of the adsorption of MNPs, this is based on previous research on engineering of nanomaterials in water treatment. Further, the wavenumber of the FTIR scanning of uncoated MNPs showed peaks on iron oxide which supports the results of Akchiche et al. (2021) supposition that points out the role of core material in the procedure of removal. Although uncoated MNPs were functioning well, the lysine functionalization helped to add another layer of binding metal ions potential, hence enhancing the general adsorption capacity (12). Findings of the research correlate with the overall trends in the area of heavy metal cleanup with magnetic nanoparticles. Naef et al. (2021) claim that using MNPs to remove heavy metal ions is a relatively new study field in which the potential of these materials has been demonstrated in recent years to adsorb a large number of pollutants (6). Nonetheless, as argued in the works of Oladimeji et al. (2024), Tongo and Erhunmwunse (2021), problems governing the application of traditional methods include operational cost and the requirement of large amounts of adsorbents (8), (2). By contrast, participation of MNPs coated with lysine is an easier and less costly option, because more surface and intensified adsorption ability and consequently less usage of materials and quicker processing time. Therefore, the study confirms the efficiency of lysine coated MNPs in the removal of nickel ions in the wastewater, which offers an excellent alternative to traditional approaches of removal of heavy metals. The outcomes also indicate the need to optimize other parameters, such as the concentration, contact time and nanoparticle dosage to ensure the highest removal efficiency. Upon comparison of the said findings with the existing literature it is evident that lysine coated MNPs promises to be commendable in terms of adsorption capacity, surface stability and operating efficiency present an industrially viable choice in the use of lysine coated MNPs in treatment of industrial waste waters.

Summary of the Findings

This research points out the successfulness of lysine-modified magnetic nanoparticles (MNPs) when it comes to removing nickel in wastewater where the efficiency at adsorption was exceptionally improved through the lysine functionalization. Optimization of the most important parameters including concentration of nickel and contact time and the dose of nanoparticle was critical in maximizing the efficiency of removal. The best parameters of obtaining nickel were found to be 600pC, 120 minutes of contact time, and 0.6g dosage of nanoparticle. The findings highlight the need to give due considerations to the optimization of adsorption conditions to maximize the removal efficiency and keep cost of the operation at minimum levels. In addition, the paper shows prospects of further optimization of nanoparticle coatings to other heavy metals including lead, cadmium, and mercury. This power to amend the surface characteristics of MNPs by adding various amino acids or other functional groups would increase the usage of MNPs in remediating any brand of waste products and hence a universal means of managing the industrial wastewater. Future work might be devoted to the optimization of such coatings and to investigation of their efficiency about removal of several contaminants at the same time.

Practical Implications of the Study

This study implies that lysine-coated magnetic nanoparticles (MNPs) may become one of the most beneficial approaches to treating heavy metals in the conditions of actual wastewater treatment. The lysine functionalization process is also very effective in increasing the adsorption ability of the MNPs which makes them well located to solve metal ion contamination on a large scale which is essential in industries. In contrast to the conventional practices, e.g. chemical precipitation, ion exchange, etc., MNPs are faster in terms of processing and more efficient in adsorption (6), which eliminates the necessity to use vast amounts of chemicals. In addition, they can be easily recovered and reused due to their magnetic attribute which is crucial to CP (15). Optimization research, including the one by Zhao et al. (2023), is capable of demonstrating how, at various concentrations and doses, optimization of adsorption parameters can be implemented to obtain the most notable efficiency (20). Consequently, lysine-modified MNPs provide an alternative with promising prospects of controlled environmental wastewater that is sustainable in terms of cost-effectiveness and ecological safety.

Limitations of the Study

Although the study offers encouraging findings on the use of lysine-coated magnetic nanoparticles (MNPs) to remove heavy metals, some limitations should be noted. Among the most important constraints is a controlled laboratory system that implies the application of a batch process. Continuous flow processes prevail to a larger extent in actual processing in industry thereby posing alternative challenges in the aspect of dispersion of nano-particles, contact time and recovery (7). The highly controlled environment applied in this work (steady temperatures, pH and oil stirring frequency) cannot easily be duplicated in a real-life industrial wastewater treatment plant. Also, the adsorption capacity revealed during the experiment was obtained at constant concentrations of nickel ions that might not parallel the dynamic concentrations and the existence of various contaminations of real wastewater (6). Moreover, the stability and reusability of lysine-coated MNPs in large-scale systems is unknown and additional investigation is necessary in order to evaluate their performance under broad operation periods and real working circumstances.

Suggestions for Further Research

Future studies could be conducted on multiple areas to further develop the feasibility in using lysine coated magnetic nanoparticles (MNPs) to purify wastewater. First, the performance of these nanoparticles in continuous flow systems needs to be investigated to more closely simulate industrial conditions where the variables (flow rate, particle dispersion and contact time) are significantly different than those associated with a batch operation (7). Also it would be useful to test the combined effect of nickel with other heavy metals and contaminants to determine the flexibility of lysine coated MNPs in treating various waste water mixtures (6). Investigations are required over the extended period of time to assess the reusability and stability of lysine-coated MNPs in the real conditions of operating with multiple adsorption-desorption runs and the influence of the additional parameters as temperature variation, changes in pH, organic matter presence (15). Also, it would be vital to examine the scalability of the reduction process so that these nanoparticles could be commercialized by producing them in large volumes at a reduced cost (13). Lastly, there would be environmental impact assessments such as whether the lysine-coated MNPs would be toxic once discarded, which would determine whether this technology would be sustainable on a mass industrial scale.

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