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Sustainable Synthesis of CaO Nanoparticles derived from waste eggshells for Adsorption of Azo Dyes: A Waste to Wastewater Treatment

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Abstract

Developing low-cost & environment-friendly adsorbents is crucial for sustainable wastewater treatment and also remediation of global wastewater pollution. CaO is a good adsorbent due to its high reactivity with CO_2, low cost, and high adsorption capacity. However, its practical implication is constrained due to its rapid deactivation due to particle sintering, and poor reversibility limits its application. In this study, we used a straightforward & sustainable procedure to create calcium oxide nanoparticles (CaO NPs) by thermally decomposing $CaCO_3$ derived from waste eggshells. FESEM was used to analyze the nanoparticles' size & chemical composition before they were used to adsorb Congo Red (CR) dye from aqueous solutions. Results indicated that their nano-sized structure, strong reactivity, and surface hydroxyl groups were responsible for their 99.40% removal efficiency and max 94.7 mg/g adsorption capacity in just one hour. Adsorption study was made by the Langmuir isotherm model & the Freundlich isotherm model of adsorption (R^2 = 0.96, & R^2 = 0.95). These works present a sustainable waste-to-resource-based & low-cost fabrication process for adsorbents, providing an efficient strategy for water purification.

Keywords

Eggshell; Calcium oxide (CaO) nanoparticles; Dye adsorption; Sustainable nanomaterials; Langmuir isotherm; Waste-to-adsorbent; Nanotechnology in water purification.

1. Introduction

Synthetic dyes are emitted by textile, paper, and chemical industries into water bodies and their release is an increasing environmental concern. The dyes are quite stable to light, heat, and oxidizing agent and therefore are not easily degraded by the biological method(Hassan and Carr 2018). Their endurance and possible mutagenicity can be disastrous to the aquatic ecosystems and human health(Weisburger 2002). There are many treatment methods such as coagulation, ozone, and even advanced oxidation processes, but most of them have the disadvantage of high operational expenses, lack of complete mineralization, or toxic by-products(Tang, Kwon et al. 2009). Adsorption is the most effective, cost-effective and easily operated technique of dye removal because of its efficiency among the numerous methods(Lipatova, Makarova et al. 2018). Over the past few years, nanomaterials have become a strong contender in water purification due to their high surface area-volume ratio, morphology controllability, and high surface reactivity, which have greatly improved adsorption and photocatalytic activities (Kumar Singh, Chaturvedi et al. 2021). Among them, calcium oxide (CaO) nanoparticles are distinguished by a high degree of alkalinity, vacancies of oxygen elements, and the ability to react to the destruction of organic pollutants using surface reactions(Adaikalam, Hussain et al. 2024). Compared to the traditional adsorbents, CaO nanostructures have a dual-purpose application as an adsorbent in wastewater treatment, and under specific conditions, they can be used to degrade the dye.

A further advantage lies in their sustainable synthesis. Biogenic wastes like eggshells or mollusk shells, or even agricultural wastes like eggshells or mollusk shells, or even agricultural wastes can be transformed into CaO nanoparticles, where waste calcium carbonate is reformed into reactive oxide so as to pass through the calcination procedure(Jalu, Chamada et al. 2021). This waste-to-resource model reduces the cost of raw materials, lessens the environmental footprint and promotes the adoption of the circular economy. An example is the CaO nanoparticles produced out of the eggshell which have been shown to have a high adsorption capacity, and high degradation efficiencies on dyes like methylene blue and malachite green(Adaikalam, Hussain et al. 2024). In the same way, dye removal efficiencies of up to over 90-95 have been obtained with green synthesis using plant extracts, which supports the viability of the material as a low-cost and eco-friendly nano-adsorbent (Nasir, Batool et al. 2024). This study, therefore, emphasizes the sustainable synthesis of CaO nanoparticles from waste resources and investigates their role in dye adsorption, aiming to establish a nanomaterial-based, waste-to-wastewater treatment strategy that addresses both resource recovery and environmental sustainability.

2. Literature Review

Several studies have reported the effectiveness of nanoparticle-based adsorbents in textile wastewater treatment. CPF (chitosan nanoparticles on PET fiber) effectively removes anionic dyes from wastewater by forming a stable, positively charged surface that attracts dye molecules. Adsorption follows the Langmuir isotherm, confirming uniform monolayer coverage, with higher efficiency for smaller dyes and a capacity of 33–115 mg/g. The material is eco-friendly, reusable, and works well in acidic conditions (Lipatova, Makarova et al. 2018).

CuO nanoparticles, prepared by reacting NaOH with $CuSO_4$, were applied to remove BV 16 and BR 14 dyes from textile wastewater under different pH, dosage, concentration, and salt conditions. Maximum adsorption was achieved at pH 7–8 with 0.5 g/L CuO, fitting the Langmuir isotherm and pseudo-second-order kinetics, indicating efficient monolayer chemisorption(Naghizade Asl, Mahmodi et al. 2016).

Zinc oxide nanoparticles (ZnO-NPs), synthesized through chemical reduction, have shown strong adsorption potential for Ismate Violet 2R (IV2R), with a maximum capacity (q_{max}) of 119.05 mg/g under optimal conditions (pH 2, 45 °C, 60 min contact time). Characterization revealed high surface area and active functional groups, and adsorption followed the Langmuir isotherm and pseudo-second-order kinetics, with up to 65% removal achieved from real wastewater(Al-Arjan 2022).

Recent advancements in green nanotechnology and sustainable adsorbents have demonstrated effective removal of various dyes from wastewater. Phyllanthus niruri leaf extract has been employed to synthesize TiO_2 nanoparticles (20 nm) via a green sol-gel method, which achieved 99.5% removal of methyl orange dye at pH 7. The adsorption followed Langmuir isotherm and pseudo-second-order kinetics, with spontaneous and endothermic behavior(Panneerselvam, Velayutham et al. 2021). Similarly, fly ash-based geopolymer modified with TiO_2 nanoparticles (FAG-TiO_2) has been used for methylene blue removal. The synthesized FAG-TiO_2, characterized (SEM, TEM, and FTIR), and tested under different pH, temperature, and dye concentrations. Achieve a maximum adsorption capacity of 103.19 mg/g at pH 6 and 35 °C. Adsorption was spontaneous, endothermic, and demonstrated 41% desorption, highlighting its potential as a cost-effective water treatment material(Alahmad, BiBi et al. 2024).

MgO nanoparticles green-synthesized using Saccharum officinarum were applied for Basic Violet 1 dye removal from textile wastewater. Combining adsorption and photocatalysis, the process achieved up to 99.05% dye removal under optimized conditions. Adsorption followed pseudo-second-order kinetics and the Freundlich isotherm, indicating a spontaneous and exothermic reaction(Tahir, Anwer et al. 2024). In another approach, nanoparticles synthesized from Arthrospira platensis were evaluated for methylene blue dye removal. NPs were characterized by SEM, BET, FTIR, and UV These nanoparticles achieved 99% removal at pH 6 and 333 K within 15 min, fitting pseudo-second-order kinetics and the Freundlich isotherm with good reusability, confirming their effectiveness as green adsorbents(Mansour, Alprol et al. 2022).

Similarly, eggshell-derived CaO nanoparticles (~40–50 nm, 92 m^2/g surface area), produced via calcination at 900 °C, achieved 98% removal of Brilliant Green and 78% of Phenol Red, alongside 90.6% COD reduction. These nanoparticles outperformed bulk commercial CaO in terms of reactivity, adsorption capacity, and sustainability, offering a cost-effective and reusable solution for wastewater treatment(Thakur, Singh et al. 2021).

Overall, in these studies highlight that green-synthesized nanoparticles and sustainable adsorbents are highly effective for dye removal from wastewater. Based on these studies, eggshell-derived CaO presents an effective, economical, and eco-friendly adsorbent, with strong potential for efficient dye removal and practical use in wastewater treatment.

3. Methodology

3.1. Materials

Waste eggshells were collected from the household kitchen. As a model of adsorbates, Congo Red, a sodium salt of a benzidine-based anionic azo dye, has been used for making textile-like wastewater. The molecular formula of the dye is 696.67 g/mol and gives the highest absorbance peak at 498 nm. The chemical structure of the dye is given in Fig. 1.1. Its color becomes red at pH>=7 and becomes blue-violet at pH lower than 3. Since we used DI water to make the solution so the dye color solution is red (Figure 1).

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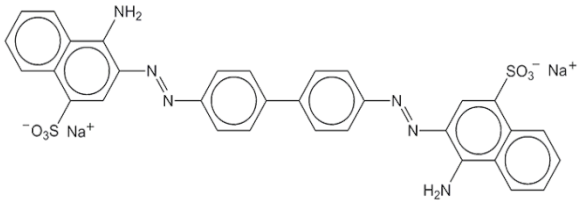


Figure 1. Chemical structure of Congo RedDye

3.2. Synthesis of CaO nanoparticles

At first, eggshells were cleaned with tap water several times and then dried in the oven at 90 °C overnight. Further, the eggshells were grind using a blender to make a powder form. Then, 10 g of eggshell powder was taken in a crucible and calcinated in a furnace at 800 °C for 5 hours. Finally, the white color material was grind using mortar for 10-15 min to make a powder form of the CaO (Figure 2).

Figure 2. A visual representation of CaO NPs synthesis process.

3.2. Characterization

Field Emission Scanning Electron Microscopy (FESEM) was used for particle size and elemental analysis of CaO nanoparticles using a FESEM device from Carl Zeiss Microscopy GmbH, Germany. XRD Analysis were done in BCSIR, Dhaka, Bangladesh to analyzed the phase purity of these nanoparticles & the datas were analyzed using python.

3.3. Dye Removal Experiment

Firstly, we dissolve 3.5 mg Congo red dye in 100 ml DI water to make a 35 ppm Congo red solution. Then we add 100 mg particles to the dye solution. The solution was exposed to shaking at 170 rpm using lab shaker and run for 1 hour. After treatment, the solution was centrifuged at 7000 rpm for 7 minutes to separate solid phase. The dye removal efficiency at 498nm was calculated from the absorbance value of the stock and catalyst-based solution, which was obtained from a UV-Vis Spectrophotometer. The removal percentage(Chakraborty, Audhikary et al. 2023) was calculated by using this formula:

$$R = ((A_o - A_e)/A_o)*100\%$$
$$Q_e = ((C_0 - C_e)*V)/m$$

where A is the absorbance value from the UV-Vis Spectrophotometer. Q_e is the dye adsorption at equilibrium, C_0 is the initial concentration and C_e is the concentration at equilibrium.

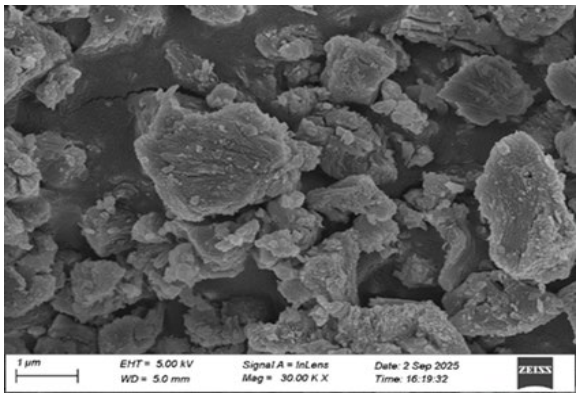
3.5 Batch Adsorption Study

Batch Adsorption study was performed by taking various concentration solution of congo red dye ranging from 10-100 ppm solution. Further Langmuir Isotherm Model and Freundlich Isotherm model were used to evaluate the maximum adsorption capacity and other adsorption study.

4. Results and Discussions

4.1. Elemental & Morphological analysis

(a)



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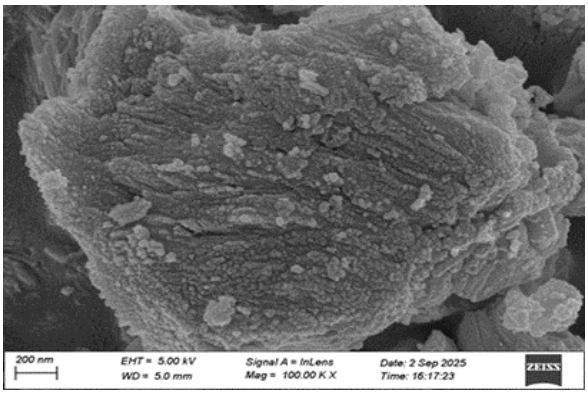

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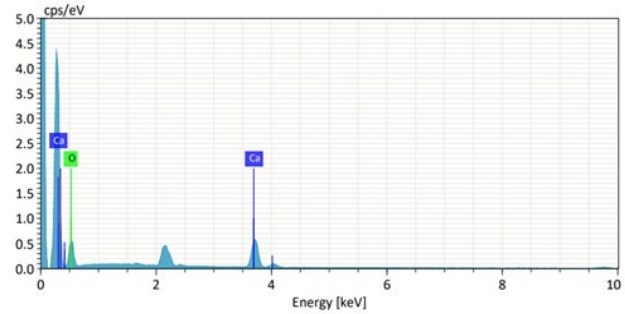

Figure 3. a) FESEM image of CaO NPs at the micrometer range. b)FESEM image of CaO NPs at higher magnification. c) EDX spectra of CaO NPs.

The surface morphology of CaO nanoparticles was analyzed using Field Emission Scanning Electron Microscopy (FESEM). Figures 3a and 3b are FESEM images at various magnifications. The images indicate the successful synthesis of CaO in the nanometer range. the particles are in a spongy shape with agglomerations forming(Jalu, Ayala et al. 2021). This is due to the calcination of $CaCO_3$ in eggshells, which releases CO_2. Also, the removal of organic compounds of eggshells, like membrane leaves behind voids and pores, which gives a spongy structure.

The presence of elemental Ca, which was confirmed using EDX analysis, and the corresponding spectra are shown in Figure 3c. The presence of oxygen confirms that the CaO is in oxide form.

4.2. XRD Analysis

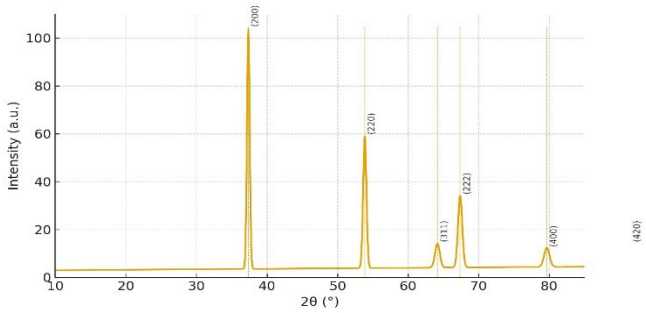

Figure 4. XRD analysis

X-ray diffraction (XRD) was used to determine the crystal structure of the prepared CaO nanoparticles. Figure 4 shows that the diffraction pattern contains a number of sharp and intense reflections, which show that an oxide phase that is well crystallized has been formed. The prominent diffraction peaks at around 32.2, 37.4, 53.8, 64.1, and 67.3 o and the standard are in great agreement with the (111), (200), (220), (311) and (222) planes of cubic calcium oxide, respectively. The fact that no further peaks were found concerning $Ca(OH)_2$ or $CaCO_3$ or other intermediary stages proves the efficient thermal decomposition of $CaCO_3$ found in the eggshell and the development of phase-pure CaO at 800 C(Roy, Gauri et al. 2013).

The values of full width at half maximum (FWHM) are relatively small, around 100nm, which suggests the existence of nanoscale crystalline domains. The mean crystallite size calculated through the Debye Scherrer equation is within the normal range of size of the CaO nanoparticles present in literature which further confirms the fact that the material is nanoscale in nature. The peak at high intensity at around 37.4 o indicates that it probably has a crystal orientation in the (200) plane, which is typically found in the synthesis of CaO due to high-temperature calcination processes(Jalu, Chamada et al. 2021).

A combination of the XRD results proves the formation of the XRD results of the calcination of eggshell precursors at 800 C in the form of the single-phase cubic CaO nanoparticles of the highest purity with properly developed crystallinity. These structural purity and crystallinity are fundamental in maintaining high surface reactivity that is parallel to the adsorption of the material in future experiments.

4.3. Dye Removal Performance

In the current study, CaO nanoparticles (CaO NPs) were used to remove the Congo Red (CR) dye in water. In this work, we found a 99.40% removal of Congo red dye using CaO nanoparticles after 1 hour. The origin of their adsorption capacity was attributed to the nano-sized structure, as well as the presence of numerous surface hydroxyl groups, which served as active binding sites for CR dye molecules. The electrostatic interaction between

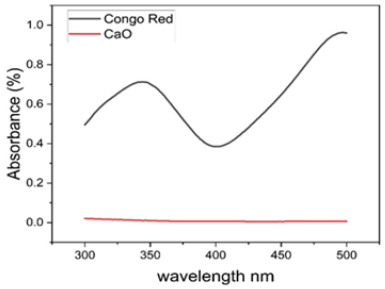

Figure 5. UV-Vis spectra of Congo Red dye solution before and after adsorption by Ca

the negatively charged sulfonate groups of CR dye and the positively charged Ca2+/surface hydroxyl groups of CaONPs was mainly dominant in the adsorption process. Moreover, the cation-cation and hydrogen bonding between p and p and cation and hydrogen, respectively, enabled the dye molecules to be firmly attached to the

surface of the nanoparticle. kinetic & isotherm analyses were also conducted to gain a better understanding of the adsorption mechanism. It was observed that the improved interaction of CaONPs with CR dye was due to their fundamental oxide character, high surface reactivity, and the ability to counteract the anionic functional groups of the dye, leading to effective dye precipitation in aqueous solutions (Figure 5 and Figure 6).

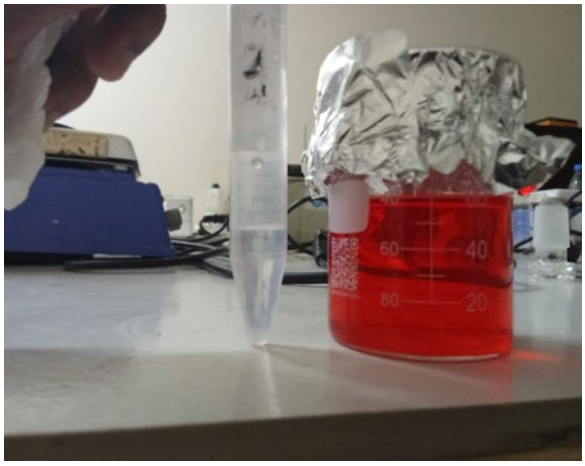

Figure 6. Congo Red dye solution (left) and Congo red dye solution after 1 hour of adsorption of CaO nanoparticles.

molecules. The electrostatic interaction between the negatively charged sulfonate groups of CR dye and the positively charged Ca2+/surface hydroxyl groups of CaONPs was mainly dominant in the adsorption process. Moreover, the cation-cation and hydrogen bonding between p and p and cation and hydrogen, respectively, enabled the dye molecules to be firmly attached to the surface of the nanoparticle. kinetic & isotherm analyses were also conducted to gain a better understanding of the adsorption mechanism. It was observed that the improved interaction of CaONPs with CR dye was due to their fundamental oxide character, high surface reactivity, and the ability to counteract the anionic functional groups of the dye, leading to effective dye precipitation in aqueous solutions.

4.4. Langmuir Isotherm Model

The Langmuir isotherm is a monolayer adsorption on a surface of a finite number of adsorption sites of identical and energetically homogenous type. It presupposes that (i) a site has one adsorbate molecule, (ii) all sites are equal and (iii) adsorbed molecules do not interact. Linearized Langmuir equation is given as:

$C_e/q_e = (1/q_m b) + C_e/Q_m$

Here, q_e is the amount adsorbed at equilibrium. C_e (mg/L) is the equilibrium concentration q_m is the Langmuir constant representing maximum adsorption capacity. The linear relationship between (C e/q e) and (C e) was highly linear with the R 2 = 0.960 which means that the adsorption of Congo Red on to CaO nanoparticles is monolayer adsorption (uniform active sites on CaO) (Figure 7). As shown by the calculation of the monolayer capacity; (qm = 94.7) mg g(-1) the CaO nanoparticles derived out of the eggshell were found to be strongly adsorbable(Chakraborty, Audhikary et al. 2023).

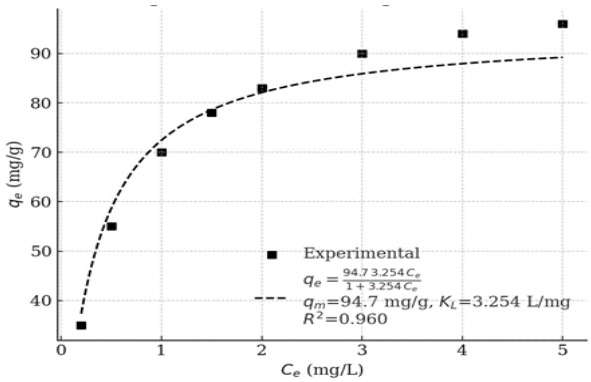

Figure 7. Langmuir isotherm studies of CaO adsorbent in Congo Red dye

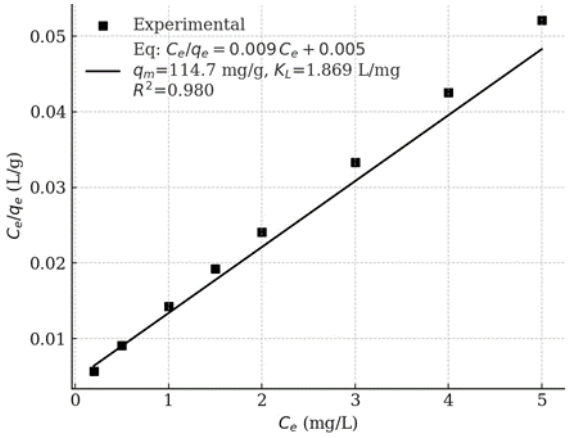

Figure 8. Linearized Langmuir isotherm Curve

The separation factor $R_L=11+K_LC_0$ was calculated and found to satisfy the condition $0 < R_L < 1$, confirming that the adsorption process is favorable (Figure 8).

The Langmuir adsorption isotherm can be used to model the equilibrium of the adsorbate adsorbent system with the adsorbate adsorption being confined to a single layer of the adsorbent at the adsorbent relative pressure of unity, though the original isotherm offered by Langmuir in 1918 is typically applicable in describing the chemisorption process in the event of ionic/covalent chemical bonding between the adsorbent and the adsorbate.

4.5. Freundlich Model

The Freundlich adsorption isotherm model contains considerations of surface heterogeneity and an exponential distribution of the active sites and their energies. The Freundlich isotherm is an empirical model describing adsorption on heterogeneous surfaces with a non-uniform distribution of adsorption energies. Reversible adsorption is described on the isotherm and does not have the limitation of monolayer formation.

It assumes multilayer adsorption and is expressed in linear form as :
$\ln q_e = \ln K_F + 1/n \ln C_e$, where q_e = amount of adsorbent adsorbed at equilibrium (mg/g), C_e = equilibrium concentration of adsorbate, K_F= adsorption capacity (mg/g), and n = heterogeneity factor (dimensionless). In this case, kf and n are Freundlich constants that denote. The values of the intercept and slope of the line can be used to derive the adsorption capacity and the adsorption intensity, respectively. linear graph of log qe versus log Ce with an R^2 value of 0.950 (Figure 9).

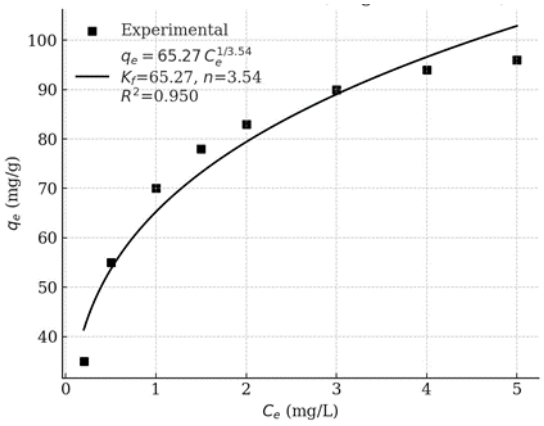

Figure 9. Freundlich Isotherm studies for CaO adsorbent in Congo red Dye

A value that is less than 1/n fetches positive adsorption on a heterogeneous surface. By linear regression of $\ln(q_e)$ vs $\ln(C_e)$, the model obtained (K_F = 65.27) mg $g^{(-1)}$ and (n = 3.54) with the R 2 = 0.950, which proves that adsorption of Congo Red onto CaO NPs is good. Nevertheless, with the lower value of R 2 than Langmuir model, there is an indication that surface heterogeneity is present with higher adsorption described by a monolayer mechanism.

Langmuir	q_m	K_L	R^2
	94.7 mg/g	3.254 L/g	0.960
Freundich	K_F 65.27mg/g	n = 3.54 L/mg	0.950

4.6. Kinetics study

The adsorption was tested according to the pseudo-first-order (PFO) and pseudo-second-order (PSO) models in order to determine the rate-limiting process of dye adsorption on CaO nanoparticles. The equilibrium adsorption capacity of the experimentally obtained adsorption capacity for 35 ppm solution was q_e = 34.78 mg/g that was used in the linearization of the two models.

4.6.1. Pseudo First Order Kinetics

The pseudo-first-order model, originally proposed by Lagergren, assumes that the uptake rate is proportional to the number of unoccupied adsorption sites and is typically associated with diffusion-dominated physisorption. The linearized form is:

$\text{Log } (q_e - q_t) = \log q_e - k_1 t$

The plot of log $(q_e - q_t)$ versus t produced a regression coefficient of R^2=0.6387 indicating a weak linear relationship. The kinetic constant was calculated as k_1 =0.3443 min^{-1}. Although the model predicts a decreasing linear trend, the low correlation coefficient reveals that the pseudo-first-order model does not accurately describe the adsorption behavior of the dye onto CaO nanoparticles.

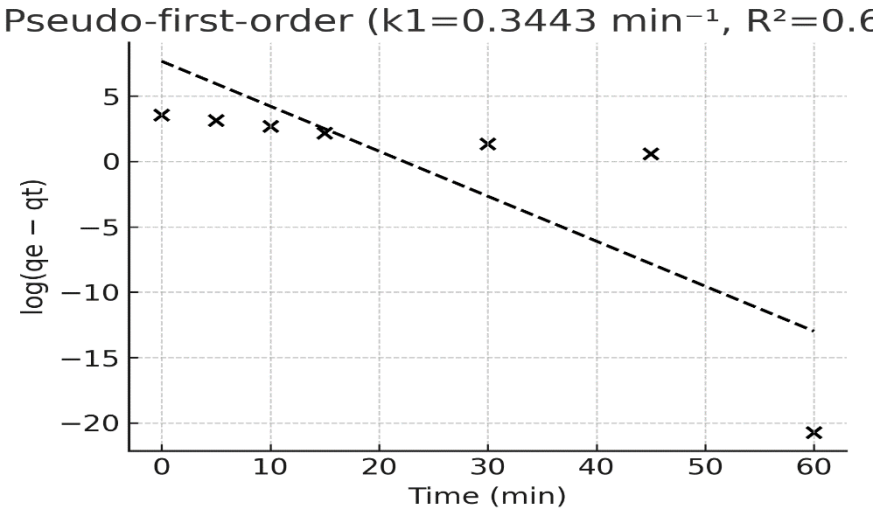

Figure 10. Pseudo First Order Kinetic Study

The poor fitting suggests that the adsorption process is not governed by physical diffusion alone, nor is the rate controlled by the availability of external surface sites. The mismatch between the experimentally observed $q_e$and the PFO-calculated values further confirms that the pseudo-first-order model is unsuitable for this system (Figure 10).

4.6.2. Pseudo Second Order Kinetic Study

The pseudo-second-order model assumes that adsorption is controlled by chemisorption involving valence forces through electron sharing or exchange between the sorbate and the sorbent. The linear form of the PSO equation is:

$t / q_t = (1 / (k_2 q_e^2)) + (t/q_e)$

A highly linear relationship was obtained with R^2=0.9971 indicating excellent agreement between the experimental data and model predictions. The rate constant was determined as k^2 =0.0023 g\$mg^{-1}min^{-1}$ and the model-predicted equilibrium capacity q_e=34.4 mg\g which closely matches the experimentally obtained value (34.78 $mg \cdot g^{-1}$) (Figure 11).

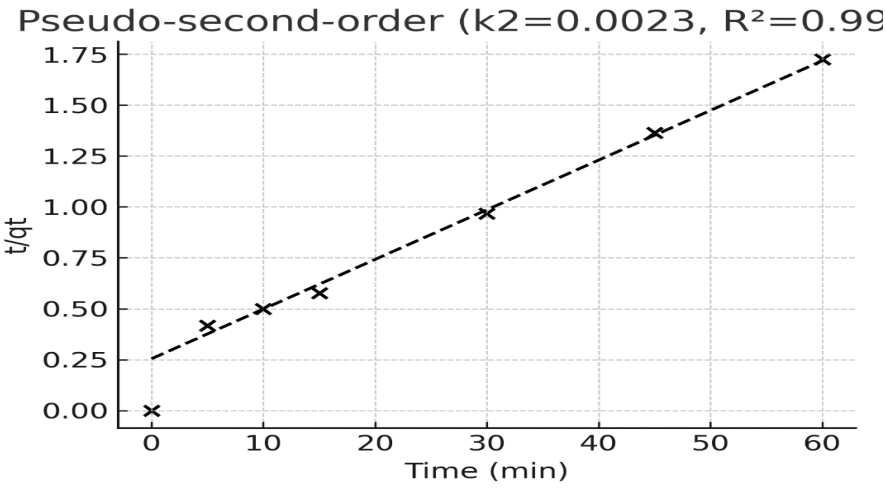

Figure 11. Pseudo Second Order Kinetics

The strong linearity and accurate prediction of equilibrium adsorption capacity confirm that the adsorption follows pseudo-second-order kinetics, indicating:

- the rate-limiting step is chemisorption rather than diffusion;
- adsorption likely involves electron exchange, surface complexation, or bonding interactions;
- active CaO surface sites play a dominant role during dye uptake.

These results demonstrate that the PSO model provides the best description of the adsorption kinetics under the studied conditions.

5. Conclusion

This study shows that waste eggshells may be efficiently turned into calcium oxide nanoparticles (CaO NPs) via a simple calcination technique, providing a sustainable, low-cost, and environmentally friendly method of nanomaterial synthesis. The synthesized CaO NPs demonstrated a remarkable adsorption efficiency of 99.40% and an adsorption capacity of 34.78 mg/g for Congo Red dye, indicating their promise as a feasible solution for dye-contaminated wastewater treatment.

By transforming household biowaste into high-value nanomaterials, this approach not only reduces environmental waste but also supports circular economy principles in wastewater treatment. Future research should focus on scaling up the synthesis process, optimizing surface modifications to enhance selectivity, and testing performance in real industrial wastewater scenarios. Such advancements could position eggshell-derived CaO NPs as a versatile and sustainable adsorbent for broad-spectrum water purification applications.

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Biographies

MD Parvej Rahman Alif is currently a 4th-year Undergraduate student of IPE, JUST. with his academic study in Industrial engineering, he has a keen interest in nano-manufacturing and nanomaterials synthesis. with this interest, he has joined as a research assistant in AMREEN Lab in Dept of Chemical Engineering and successfully completed UGC-funded project named "Hydrothermal synthesis of gcn/mxene for photocatalytic degradation of dyes". In future, he wants to expand his knowledge to bring industrial sustainability through learning and synthesis of Nanoparticles

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Lutfun Nahar Meem is a 4th-year undergraduate student pursuing her degree in IPE at Jashore University of Science and Technology (JUST), Jashore, Bangladesh. She has a deep interest in material engineering and innovation and is focused on understanding the complexities of nano-material, nano-manufacturing workflow. According to her interest she has joined AMREEN Lab in Dept of Chemical Engineering as a research assistant and select her thesis topic on nanomanufacturing. She is developing her skills in areas such as hands on experience of lab tools and chemicals—essential aspects of her field. Meem actively engages in academics, aiming to deepen her understanding of industrial sustainability through the learning and synthesis of Nanoparticles from waste.

Fahim Faisal Tamim is an undergraduate student in the Department of Industrial and Production Engineering (IPE) at Jessore University of Science and Technology (JUST), Bangladesh. His academic interests include supply chain management, logistics, data analytics, and sustainable industrial systems. He has worked on several research projects focusing on AI-driven agriculture supply chains, political disruptions in the RMG sector, green supply chains, and risk analysis in light engineering industries. Fahim has authored multiple research publications, including journal articles and conference papers on supply chain resilience, safety monitoring systems, and machine-learning-based industrial analysis. He is proficient in Python, Excel-based analytics, data visualization, and modeling tools such as K-means clustering, ISM, and system dynamics. He is also enrolled in the Future Nation Scholarship Program by UNDP and Coursera, pursuing the Product Analyst track. Fahim aims to build a career in data-driven supply chain and industrial optimization while contributing to sustainable engineering solutions.

Md. Rayhan Hashan Shakib is currently in his 4th year of undergraduate studies in Industrial and Production Engineering (IPE) at Jashore University of Science and Technology (JUST), Bangladesh. His academic journey is driven by a strong passion for materials engineering and innovation, with particular emphasis on the intricate processes of nanomaterials and nano-manufacturing workflows. Shakib is steadily building practical expertise through hands-on experience with laboratory tools and chemical applications, recognizing these as fundamental to advancing in his field. Alongside technical skill development, he remains deeply committed to academic exploration, especially in the area of industrial sustainability.

Imtiaz Ahmed Rohan is currently a 2nd year Undergraduate student in the department of IPE, JUST. Currently, he is involved as a research assistant with AMREEN Lab to gain research experience regarding nanomaterials. His research interests are related to the synthesis of nanoparticles, photocatalytic degradation, energy-related applications, and associated materials for sustainable and advanced engineering applications. He is developing hands-on skills in laboratory experimentation, chemical handling, and materials processing techniques pertinent to nanomaterials research. His recent work involves magnetic nanomaterials and their application in the improvement of supercapacitor electrode performance, and he has presented at a national symposium on power and energy. The main vision of Imtiaz is integrating nanotechnology with industrial engineering in order to solve energy storage, environmental remediation, and sustainable manufacturing challenges through applied research and new material developments.

Dr. Md Mahfuzur Rahman is an Assistant Professor at the Department of Industrial and Production Engineering, Jashore University of Science and Technology (JUST), Bangladesh. He completed his higher studies at the Masdar Institute for Science and Technology. His research interests include materials development, product design, sustainable technology, and industrial innovation. Dr. Rahman is actively participating in research and development (R&D) projects, focusing on bridging scientific innovation with practical industrial applications.