

# GREEN SYNTHESIS OF NANO-ZERO-VALENT IRON USING CLEISTOCALYX OPERCULATUS EXTRACT FOR EFFICIENT RHODAMINE B DEGRADATION

Duc Thieu Nguyen<sup>1</sup>, Thi Bich Phuong Nguyen<sup>2</sup>, Phuong Hien Ho<sup>2</sup>,  
Van Bang Nguyen<sup>3</sup>, Thi Phuong Nguyen<sup>3</sup>, Van Chinh Tran<sup>3,\*</sup>

<sup>1</sup>Hanoi University of Industry

<sup>2</sup>Hanoi National University of Education

<sup>3</sup>Institute of Materials, Biology and Environment, Academy of Military Science and Technology

## Abstract

In this study, nano-zero-valent iron (nZVI) was successfully synthesized via a green method using *Cleistocalyx operculatus* leaf extract as a natural reducing agent. The synthesized nZVI was characterized by XRD, SEM-EDS, FT-IR, and BET analyses. The XRD pattern confirmed the formation of crystalline  $\alpha\text{-Fe}^0$  while SEM images revealed spherical aggregates in the 50-100 nm size range. FT-IR analysis identified organic functional groups from the plant extract on the nanoparticle surface, indicating bio-capping. BET analysis showed a specific surface area of 67.484 m<sup>2</sup>/g with a mixed micro-mesoporous structure. Batch degradation experiments were conducted at an initial Rhodamine B (RhB) concentration of 10 mg/L, using an nZVI dose of 0.3 g/L, H<sub>2</sub>O<sub>2</sub> dose of 0.01 M, and initial pH of 7.0. Results demonstrated that nZVI alone mainly adsorbed RhB, whereas H<sub>2</sub>O<sub>2</sub> alone exhibited limited oxidation. In contrast, the combined nZVI/H<sub>2</sub>O<sub>2</sub> system achieved nearly complete decolorization within 50 min, following a pseudo-first-order kinetic model with an apparent rate constant of 0.083 min<sup>-1</sup>. The enhanced efficiency was attributed to a heterogeneous Fenton-like process generating highly reactive ·OH radicals. These findings highlight that *C. operculatus*-mediated nZVI provides a sustainable and efficient strategy for the removal of organic dyes from wastewater, underscoring its promise for advanced water treatment applications.

**Keywords:** Nano-zero-valent iron; green synthesis; *Cleistocalyx operculatus*; Rhodamine B; water treatment; adsorption.

## 1. Introduction

The discharge of synthetic dyes into water bodies poses serious environmental and health risks due to their toxicity, persistence, and resistance to conventional treatment processes. Among them, Rhodamine B (RhB), a xanthene dye widely used in textiles, cosmetics, and analytical laboratories, is of particular concern because of its high stability, potential carcinogenicity, and adverse effects on aquatic ecosystems [1].

---

\* Corresponding author, email: chinhpkkq@gmail.com

DOI: 10.56651/lqdtu.jst.v3.n02.1063.pce

Developing efficient and sustainable methods for dye removal is therefore a pressing environmental challenge.

Nano-zero-valent iron (nZVI) has attracted considerable attention for water and wastewater treatment owing to its high surface reactivity, strong reducing power, and ability to activate oxidants such as hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) for the generation of hydroxyl radicals ( $\cdot\text{OH}$ ) through heterogeneous Fenton-like reactions. These reactive radicals can degrade a wide range of recalcitrant organic pollutants, including dyes, pharmaceuticals, and pesticides [2], [3]. However, conventionally synthesized nZVI often suffers from particle agglomeration, rapid oxidation, and the use of hazardous chemical reducing agents, which limit its large-scale application.

Green synthesis of nZVI using plant extracts has emerged as a promising alternative to chemical or physical routes. Plant-derived biomolecules such as polyphenols, flavonoids, and proteins can act as reducing and stabilizing agents, facilitating the formation of nanoparticles with improved stability and reduced environmental footprint. Several studies have reported successful plant-mediated synthesis of nZVI for contaminant removal, such as using *Ricinus communis* seeds extract for methylene blue degradation, or *Psidium guajava* leaves extract for antibacterial applications [4], [5]. In Vietnam, natural resources rich in polyphenols are abundant; however, their potential in green nanomaterial synthesis for water treatment remains underexplored.

*Cleistanthus operculatus*, a medicinal plant widely distributed in Southeast Asia, is known to contain diverse polyphenolic compounds with strong reducing properties. Several studies have demonstrated the effectiveness of using *Cleistanthus operculatus* extract for the green synthesis of nZVI [6], [7]. However, its potential for producing bio-capped nZVI with application in dye removal is still limited. This study addresses this gap by synthesizing nZVI using *C. operculatus* leaf extract, characterizing the structural and surface properties of the nanoparticles, and evaluating their performance in RhB removal under different treatment conditions [8], [9]. The novelty of this work lies in demonstrating the synergistic effect of nZVI and  $\text{H}_2\text{O}_2$  in achieving rapid and efficient RhB degradation through a heterogeneous Fenton-like process, highlighting the potential of *C. operculatus*-mediated nZVI as a sustainable and effective material for wastewater treatment.

## 2. Materials and methods

### 2.1. Materials

Iron (II) chloride tetrahydrate ( $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$ , > 99%), ethanol ( $\text{C}_2\text{H}_5\text{OH}$ , > 99%), and Rhodamine B (RhB) dye were purchased from Xilong Chemicals (China) and used

without further purification. Deionized water was used as the solvent. Polyphenols extracted from *Cleistocalyx operculatus* leaves, obtained from a local market, served as a green reducing agent.

### **2.2. Extraction of Polyphenols from *Cleistocalyx operculatus* leaves**

Fresh *Cleistocalyx operculatus* leaves were thoroughly washed with deionized water to remove surface impurities and then oven-dried at 60°C until constant weight. The dried leaves were ground into fine powder using a mechanical grinder. For each extraction batch, 10 g of the leaf powder was dispersed in 200 mL of deionized water and subjected to ultrasonic treatment for 1 h to enhance the extraction efficiency. The resulting mixture was then heated and magnetically stirred at 60-70°C for 30 min. After cooling to room temperature, the suspension was centrifuged at 6000 rpm for 10 min to remove insoluble residues. The supernatant was further filtered through a 40 µm PTFE membrane to obtain the final leaf extract, which was subsequently used as a green reducing agent in the synthesis of nZVI.

### **2.3. Preparation of nZVI**

A 10 mL of 0.1 M Fe<sup>2+</sup> solution was prepared by dissolving FeCl<sub>2</sub>·4H<sub>2</sub>O in deionized water. The synthesis of nZVI was carried out in a three-necked round-bottom flask equipped with a magnetic stirrer and heating mantle. The Fe<sup>2+</sup> solution was heated to 60-70°C under continuous stirring. Subsequently, 10 mL of the prepared *Cleistocalyx operculatus* leaves extract was slowly added dropwise into the solution. The reaction was allowed to proceed for approximately 30 minutes. The formation of nZVI was indicated by a distinct color change of the reaction mixture from light orange to black. Throughout the synthesis, nitrogen gas was continuously purged into the flask to minimize oxidation of zero-valent iron. After the reaction, the black precipitate was separated by centrifugation and washed three times with deionized water and twice with ethanol. The final product was dried overnight in a desiccator to obtain the nZVI particles.

### **2.4. Characterization**

The crystalline characteristics of nZVI was analyzed using X-ray diffraction (XRD) with Cu K<sub>α</sub> radiation ( $\lambda = 0.154$  nm), performed on a Bruker D8 Advance diffractometer. Surface morphology and elemental composition were investigated through scanning electron microscopy (SEM) using a Hitachi S-4600 microscope equipped with an EDS detector. Fourier-transform infrared spectroscopy (FT-IR, Bruker Tensor II) was employed to identify functional groups in the wavenumber range of 400-4000 cm<sup>-1</sup>. The specific surface area and pore structure were evaluated using nitrogen adsorption-desorption isotherms obtained with a Quantachrome NOVA Touch 2LX analyzer.

### 2.5. Batch experiments of decolorization of RhB

Decolorization of RhB experiments was carried out at room temperature and at an initial pH of 7.0. In this study, the as-synthesized nZVI, prepared according to the procedure described above, was added at a dosage of 0.3 g/L into 50 mL of RhB solution with an initial concentration of 10 mg/L. The mixture was stirred for certain period of time (10, 20, 30, 40, and 50 min), using a magnetic stirrer to find out the effect of contact time in the removal of RhB. At each time interval, a 3 mL aliquot was withdrawn and centrifuged to remove solids. RhB removal performance was evaluated under three conditions: (i) nZVI alone, (ii) 2 mL H<sub>2</sub>O<sub>2</sub> (0.01 M) alone, and (iii) a mixture of nZVI with 2 mL H<sub>2</sub>O<sub>2</sub> (0.01 M). The concentration of RhB was determined by UV-Vis spectroscopy (Drawell) at 553 nm.

## 3. Results and discussion

### 3.1. Characterization of nZVI

The XRD pattern of the synthesized nZVI (Fig. 1) exhibits two prominent diffraction peaks at  $2\theta \approx 44.9^\circ$  and  $65.4^\circ$ , corresponding to the (110) and (200) planes of body-centered cubic  $\alpha$ -Fe<sup>0</sup> (JCPDS 00-001-1267), confirming the presence of zero-valent iron. Additionally, low-intensity peaks observed at approximately  $26.7^\circ$ , and  $35.2^\circ$  are attributed to the characteristic reflections of iron oxide hydrate (FeOOH), suggesting partial surface oxidation of the nanoparticles [10], [11]. These results confirm the successful formation of crystalline nZVI, with a predominant  $\alpha$ -Fe<sup>0</sup> phase and minor oxidized species, demonstrating the effectiveness of the plant-mediated reduction approach.

Figure 1b shows the EDX spectrum of the synthesized nZVI. The main elements detected are carbon (C), oxygen (O), and iron (Fe), with weight percentages of 37.61%, 46.72%, and 15.67%, respectively. The presence of Fe peaks confirms the successful formation of iron-based nanoparticles, while the high oxygen content likely originates from surface oxidation or residual oxygen-containing functional groups derived from the plant extract. The strong carbon signal can be attributed to capping organic compounds present in the *Cleistocalyx operculatus* extract, which may contribute to the stabilization of the nZVI particles. These results are consistent with previous studies on green-synthesized nZVI, where carbon and oxygen are frequently observed as dominant surface components due to bio-organic residues and surface oxidation [12].

As shown in Fig. 2, the synthesized nZVI exhibits aggregated, roughly spherical particles with sizes ranging from 50 to 100 nm. The aggregation is typical for nZVI due to magnetic attraction and high surface energy. The surface morphology appears moderately rough, which may enhance surface reactivity. These observations are consistent with previous reports on plant-mediated nZVI, where bio-organic compounds provide partial stabilization but limited control over particle dispersion [13].

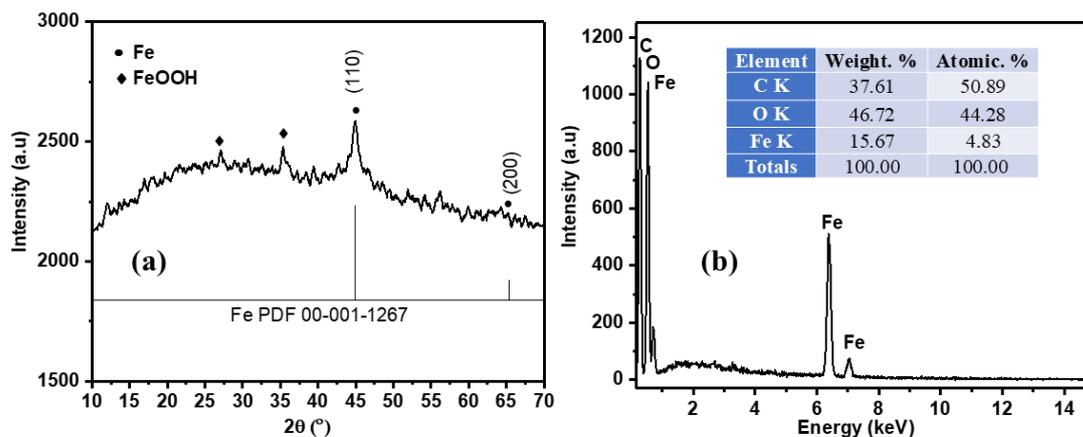


Fig. 1. (a) XRD pattern and (b) EDX spectrum of nZVI.

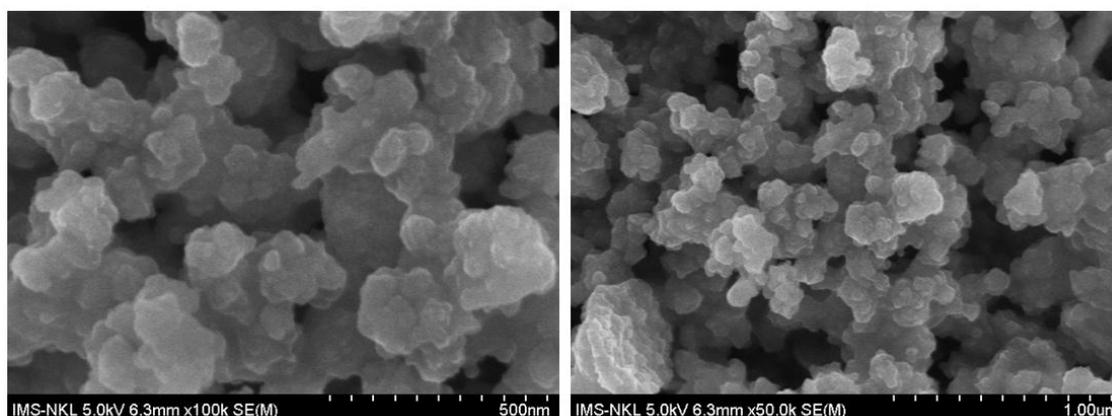


Fig. 2. SEM images of nZVI.

The FT-IR spectrum of the synthesized nZVI (Fig. 3a) reveals characteristic absorption bands associated with both organic functional groups and iron-oxygen vibrations. The peak observed at  $1572\text{ cm}^{-1}$  is attributed to C=O and/or aromatic C=C stretching, indicating the presence of polyphenolic compounds from the *Cleistanthus operculatus* extract. The bands at  $1336\text{ cm}^{-1}$  and  $1067\text{ cm}^{-1}$  correspond to C–N and C–O stretching vibrations, respectively, further confirming the existence of plant-derived organic moieties acting as capping agents. In the lower wavenumber region, absorption bands at  $761$ ,  $647$ ,  $433$ , and  $412\text{ cm}^{-1}$  are ascribed to Fe–O stretching vibrations, verifying the formation of iron nanoparticles with partially oxidized surfaces. These results are in agreement with previous studies on green-synthesized nZVI, where similar Fe–O and bio-organic functional group signals were reported in FT-IR spectra of materials synthesized using oak leaf and *Psidium guajava* extracts [5], [13]. Overall, the FT-IR findings support the presence of a bio-organic coating on the nanoparticle surface, which likely contributes to their colloidal stability.

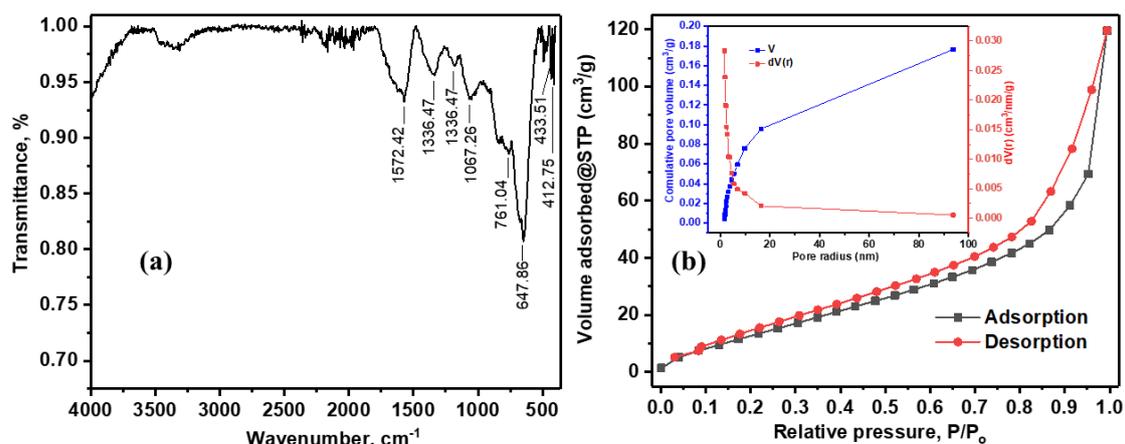


Fig. 3. (a) FT-IR spectrum, and (b)  $N_2$  adsorption-desorption isotherm and the pore size distribution (insert) of nZVI.

Figure 3b shows the nitrogen adsorption-desorption isotherm of the synthesized nZVI, which corresponds to a type IV isotherm with a clear H3 hysteresis loop according to IUPAC classification, indicating the presence of mesoporous structures formed by slit-like pores [1]. The BET surface area was calculated to be  $67.484 \text{ m}^2/\text{g}$ , with a total pore volume of  $0.176 \text{ cm}^3/\text{g}$  and an average pore radius of  $1.659 \text{ nm}$ . Although the average pore radius lies close to the boundary between micropores ( $< 2 \text{ nm}$ ) and mesopores ( $2\text{-}50 \text{ nm}$ ), the pore size distribution (inset) shows a distinct contribution from both micropores and mesopores. These features suggest that the material exhibits a micro-mesoporous structure, where slit-like mesopores coexist with significant microporosity. Such hierarchical porosity is favorable for enhancing both the reactivity and diffusion of target contaminants in environmental applications of nZVI.

### 3.2. RhB removal performance

RhB removal was evaluated under three conditions - (i) nZVI alone, (ii)  $2 \text{ mL H}_2\text{O}_2$  ( $0.01\text{M}$ ) alone, and (iii) nZVI +  $2 \text{ mL H}_2\text{O}_2$  ( $0.01\text{M}$ ) - and monitored at the time intervals indicated in Fig. 4.

The UV-Vis absorption spectra presented in Fig. 4 clearly demonstrate the distinct performance of RhB removal under different experimental conditions. When only nZVI was applied (Fig. 4a), the characteristic absorption band of RhB at  $553 \text{ nm}$  decreased only slightly with reaction time, indicating that the removal was mainly attributed to adsorption of dye molecules onto the surface of nZVI particles, with limited contribution from reductive degradation. In contrast, treatment with  $\text{H}_2\text{O}_2$  alone (Fig. 4b) resulted in a more pronounced decrease in absorbance compared with nZVI, but complete discoloration was not achieved within  $50 \text{ min}$ . After  $50 \text{ minutes}$ , the RhB degradation

efficiencies using nZVI, H<sub>2</sub>O<sub>2</sub>, and the nZVI/H<sub>2</sub>O<sub>2</sub> system were 82.16%, 70.12%, and 99.53%, respectively. This limited performance can be ascribed to the fact that H<sub>2</sub>O<sub>2</sub> alone exhibits relatively weak oxidizing ability under ambient conditions, and its decomposition rate is insufficient to generate a significant amount of hydroxyl radicals ( $\cdot$ OH) without a proper catalyst.

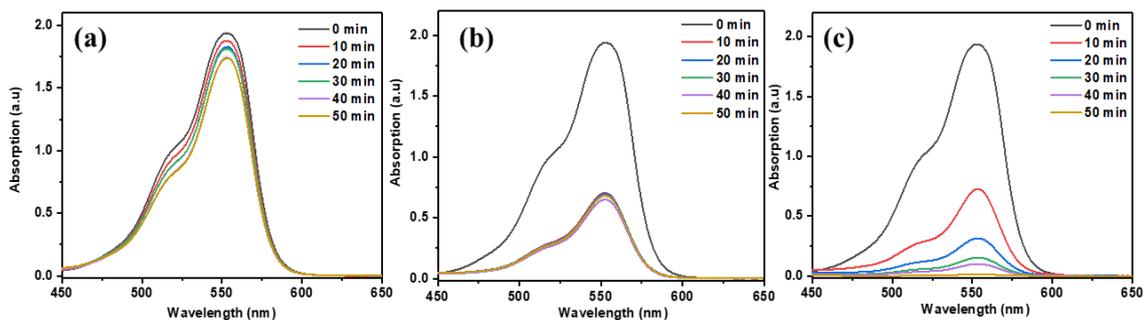


Fig. 4. UV-Vis spectra of RhB solution using (a) nZVI, (b) 2 mL H<sub>2</sub>O<sub>2</sub> 0.01M, and (c) nZVI + 2 mL H<sub>2</sub>O<sub>2</sub> 0.01M.

Notably, the combined nZVI/H<sub>2</sub>O<sub>2</sub> system (Fig. 4c) showed a rapid and substantial reduction in the absorption intensity, leading to almost complete disappearance of the RhB peak within 50 min. This enhanced performance is attributed to the heterogeneous Fenton-like process, in which Fe<sup>0</sup> present in nZVI reacts with H<sub>2</sub>O<sub>2</sub> to generate  $\cdot$ OH radicals through redox cycling between Fe<sup>2+</sup>/Fe<sup>3+</sup>. These highly reactive species effectively attack the chromophoric structure of RhB, breaking down its conjugated system and accelerating the decolorization of the dye. Similar synergistic effects of nZVI and H<sub>2</sub>O<sub>2</sub> have been reported in previous studies, where the coupling of zero-valent iron with hydrogen peroxide significantly improved the degradation rates of various organic contaminants compared with the use of either reagent alone [3], [14], [15].

The kinetic data of RhB degradation fitted well with a pseudo-first-order model, as shown in Fig. 5. The calculated rate constants (*k*) were 0.001 min<sup>-1</sup> for nZVI, 0.017 min<sup>-1</sup> for H<sub>2</sub>O<sub>2</sub>, and 0.083 min<sup>-1</sup> for the combined nZVI/H<sub>2</sub>O<sub>2</sub> system. These results clearly indicate that nZVI alone mainly contributed through surface adsorption with negligible degradation activity, while H<sub>2</sub>O<sub>2</sub> alone exhibited only a limited oxidative effect under ambient conditions. In contrast, the nZVI/H<sub>2</sub>O<sub>2</sub> system achieved a reaction rate approximately five times higher than H<sub>2</sub>O<sub>2</sub> alone and more than eighty times higher than nZVI alone. This significant enhancement confirms the synergistic role of nZVI as a catalyst in activating H<sub>2</sub>O<sub>2</sub> to generate highly reactive  $\cdot$ OH radicals via a heterogeneous Fenton-like process, thereby accelerating the breakdown of the RhB chromophore.

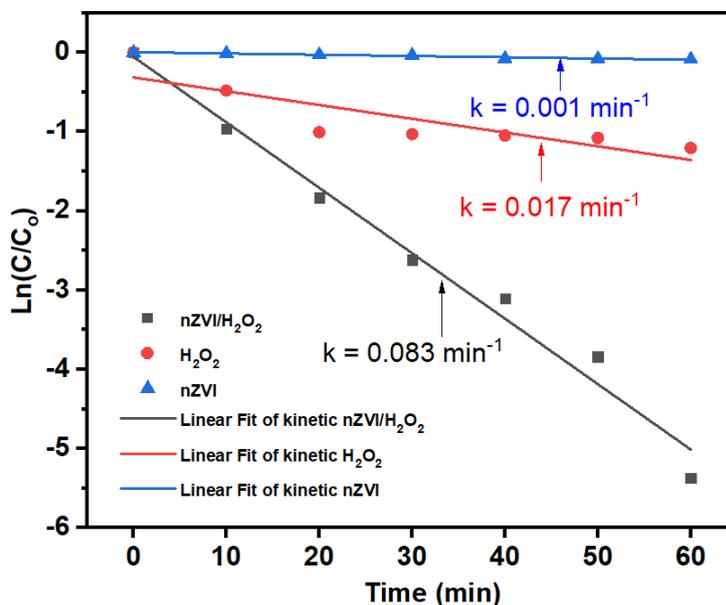


Fig. 5. Pseudo-first-order kinetic plots for Rhodamine B degradation under different treatment conditions (nZVI, H<sub>2</sub>O<sub>2</sub>, and nZVI/H<sub>2</sub>O<sub>2</sub>).

Overall, the superior performance of the nZVI/H<sub>2</sub>O<sub>2</sub> system highlights its potential as an efficient advanced oxidation process for wastewater treatment. The results not only confirm the pivotal role of ·OH radicals in dye degradation but also provide further evidence supporting the application of heterogeneous Fenton-like reactions in the removal of recalcitrant organic pollutants

#### 4. Conclusion

Nano-zero-valent iron (nZVI) was successfully synthesized using *Cleistanthus operculatus* leaf extract, yielding crystalline α-Fe<sup>0</sup> nanoparticles with partial surface oxidation and bio-organic stabilization. The material exhibited favorable surface area and porosity, supporting efficient contaminant interaction. Batch experiments showed that the nZVI/H<sub>2</sub>O<sub>2</sub> system achieved nearly complete removal of Rhodamine B within 50 min, driven by a heterogeneous Fenton-like mechanism. These results confirm the potential of plant-mediated nZVI as a sustainable and effective material for wastewater treatment applications.

#### Acknowledgement

The authors thank the Institute of Chemistry and Materials for providing equipment for the research project.

## References

- [1] C. V. Tran *et al.*, “New TiO<sub>2</sub>-doped Cu–Mg spinel-ferrite-based photocatalyst for degrading highly toxic rhodamine B dye in wastewater”, *Journal of Hazardous Materials*, Vol. 420, 2021. DOI: 10.1016/j.jhazmat.2021.126636
- [2] M. Stefaniuk, P. Oleszczuk, and Y. S. Ok, “Review on nano zerovalent iron (nZVI): From synthesis to environmental applications”, *Chemical Engineering Journal*, Vol. 287, pp. 618-632, 2016. DOI: 10.1016/j.cej.2015.11.046
- [3] Y. Segura, F. Martínez, and J. A. Melero, “Effective pharmaceutical wastewater degradation by Fenton oxidation with zero-valent iron”, *Applied Catalysis B: Environmental*, Vol. 136, pp. 64-69, 2013. DOI: 10.1016/j.apcatb.2013.01.036
- [4] M. Dinsa and K. Mequanint, “Sustainable and green synthesis of nano zero-valent iron for hexavalent chromium adsorption”, *ACS Omega*, Vol. 10, Iss. 27, pp. 29306-29316, 2025. DOI: 10.1021/acsomega.5c02281
- [5] J. Jeyasundari *et al.*, “Green synthesis and characterization of zero valent iron nanoparticles from the leaf extract of Psidium guajava plant and their antibacterial activity”, *Chemical Review and Letters*, Vol. 6, No. 22, pp. 1244-1252, 2017.
- [6] N. T. Le *et al.*, “Green synthesis of highly stable zero-valent iron nanoparticles for organic dye treatment using *Cleistocalyx operculatus* leaf extract”, *Sustainable Chemistry Pharmacy*, Vol. 25, 2022. DOI: 10.1016/j.scp.2022.100598
- [7] P. T. H. Nguyen *et al.*, “Green synthesis of biogenic nano zerovalent iron using *Cleistocalyx nervosum* leaf extract for enhancing peanut seed germination and basella alba growth”, *ACS Omega*, Vol. 10, Iss. 21, pp. 22137-22145, 2025. DOI: 10.1021/acsomega.5c02421
- [8] D. T. Thanh *et al.*, “Phytochemical composition, antioxidant, antibacterial, and enzyme inhibitory activities of organic extracts from flower buds of *Cleistocalyx operculatus* (Roxb.) Merr. et Perry”, *BioTechnologia*, Vol. 105, No. 2, pp. 137-147, 2024. DOI: 10.5114/bta.2024.139753
- [9] K. H. Le *et al.*, “Fabrication of *Cleistocalyx operculatus* extracts/chitosan/gum arabic composite as an edible coating for preservation of banana”, *Progress in Organic Coatings*, Vol. 161, 2021. DOI: 10.1016/j.porgcoat.2021.106550
- [10] A. M. Abdelfatah *et al.*, “Green synthesis of nano-zero-valent iron using ricinus communis seeds extract: Characterization and application in the treatment of methylene blue-polluted water”, *ACS Omega*, Vol. 6, Iss. 39, pp. 25397-25411, 2021. DOI: 10.1021/acsomega.1c03355
- [11] F. Ma *et al.*, “Green synthesis of nZVI-modified biochar significantly enhanced the removal of Cr(VI) from aqueous solution”, *Environmental Science Pollution Research*, Vol. 31, No. 23, pp. 33993-34009, 2024. DOI: 10.1007/s11356-024-33553-x
- [12] A. M. Abdelfatah *et al.*, “Efficient adsorptive removal of tetracycline from aqueous solution using phytosynthesized nano-zero valent iron”, *Journal of Saudi Chemical Society*, Vol. 25, Iss. 12, 2021. DOI: 10.1016/j.jscs.2021.101365
- [13] M. Yousefi *et al.*, “Green synthesis of zero iron nanoparticles and its application in the degradation of Sulphacetamide by using of PS/nZVI process”, *International Journal of Environmental Analytical Chemistry*, Vol. 103, No. 17, pp. 5720-5733, 2023. DOI: 10.1080/03067319.2021.1942862

- [14] G. Zhao and K. Feng, "Ultraviolet-enhanced Fe<sup>0</sup>-activated H<sub>2</sub>O<sub>2</sub> process for the removal of refractory organic matter from landfill leachate: Performance and mechanism", *Water Environment Research*, Vol. 97, No. 2, 2025. DOI: 10.1002/wer.70022
- [15] S. Yang *et al.*, "Degradation of refractory organic matter in MBR effluent from treating landfill leachate by the UV-nZVI-H<sub>2</sub>O<sub>2</sub> system", *Environmental Science Pollution Research*, Vol. 30, No. 17, pp. 50295-50308, 2023. DOI: 10.1007/s11356-023-25756-5

## TỔNG HỢP XANH NANO SẮT HÓA TRỊ KHÔNG BẰNG DỊCH CHIẾT LÁ VỎI CHO HIỆU QUẢ PHÂN HỦY RHODAMINE B

Nguyễn Đức Thiệu<sup>1</sup>, Nguyễn Thị Bích Phượng<sup>2</sup>, Hồ Phương Hiền<sup>2</sup>,  
Nguyễn Văn Bằng<sup>3</sup>, Nguyễn Thị Phượng<sup>3</sup>, Trần Văn Chính<sup>3</sup>

<sup>1</sup>Đại học Công nghiệp Hà Nội

<sup>2</sup>Trường Đại học Sư phạm Hà Nội

<sup>3</sup>Viện Vật liệu, Sinh học và Môi trường, Viện Khoa học và Công nghệ quân sự

**Tóm tắt:** Trong nghiên cứu này, sắt zero hóa trị kích thước nano (nZVI) đã được tổng hợp thành công bằng phương pháp xanh sử dụng dịch chiết lá *Cleistocalyx operculatus* như một tác nhân khử tự nhiên. Vật liệu nZVI thu được được đặc trưng bằng các kỹ thuật XRD, SEM-EDS, FT-IR và BET. Giải đồ XRD xác nhận sự hình thành pha tinh thể  $\alpha$ -Fe<sup>0</sup>, trong khi ảnh SEM cho thấy các tập hợp hình cầu có kích thước trong khoảng 50-100 nm. Phân tích FT-IR nhận diện các nhóm chức hữu cơ từ dịch chiết thực vật hiện diện trên bề mặt hạt nano, chứng tỏ có lớp bao phủ sinh học. Phân tích BET cho thấy diện tích bề mặt riêng đạt 67,484 m<sup>2</sup>/g với cấu trúc vi mao quản - trung mao quản hỗn hợp. Thí nghiệm phân hủy theo mẻ được tiến hành với nồng độ ban đầu của Rhodamine B (RhB) là 10 mg/L, sử dụng liều lượng nZVI 0,3 g/L, H<sub>2</sub>O<sub>2</sub> 0,01 M và pH ban đầu 7,0. Kết quả cho thấy nZVI đơn lẻ chủ yếu hấp phụ RhB, trong khi H<sub>2</sub>O<sub>2</sub> đơn lẻ thể hiện khả năng oxi hóa hạn chế. Ngược lại, hệ kết hợp nZVI/H<sub>2</sub>O<sub>2</sub> đạt hiệu suất khử màu gần như hoàn toàn sau 50 phút, tuân theo mô hình động học giả bậc nhất với hằng số tốc độ biểu kiến 0,083 phút<sup>-1</sup>. Hiệu quả gia tăng này được quy cho quá trình Fenton dị thể tạo ra các gốc ·OH có hoạt tính cao. Những phát hiện này cho thấy nZVI tổng hợp từ *C. operculatus* mang lại một giải pháp bền vững và hiệu quả trong loại bỏ thuốc nhuộm hữu cơ khỏi nước thải, nhấn mạnh tiềm năng ứng dụng trong xử lý nước tiên tiến.

**Từ khóa:** Sắt nano hóa trị không (nZVI); tổng hợp xanh; *Cleistocalyx operculatus* (lá vối); Rhodamine B; xử lý nước; hấp phụ.

Received: 26/08/2025; Revised: 17/09/2025; Accepted for publication: 29/10/2025

