International Journal Multidisciplinary
Homepage : https://journal.antispublisher.com/index.php/IJMI
Email : admin@antispublisher.com

e-ISSN : 3031-9870
IJMI, Vol. 4, No. 1, February 2027
Page 1-10
© 2027 IJMI :
International Journal Multidisciplinary

Treatment of Industrial Wastewater Using Physical and Chemical Mechanisms and The Adsorption Properties of Nanoparticles Produced by A Green Method

Khawla S. Mohammed
Tikrit University, Iraq

Check for updates OPEN ACCESS

DOI : https://doi.org/10.61796/ijmi.v4i1.649

Sections Info

Article history:
Submitted: August 13, 2026
Final Revised: September 07, 2026
Accepted: Oktober 16, 2026
Published: November 06, 2026

Keywords:
Industrial wastewater
Green nanoparticles
Adsorption
Heavy metals
Physicochemical treatment

ABSTRACT

Objective: *Industrial effluent is one of the most serious sources of water pollution, containing heavy metal ions, as well as organic compounds, synthetic dyes and toxic substances, which are difficult to remove using conventional biological treatment.* ***Method:*** *This article examines the effective role of nanoparticles manufactured using a green process, which we utilise in the treatment of this wastewater. It focuses on the physicochemical mechanisms involved in the adsorption processes employed, such as hydrogen bonding and electrostatic attraction, as well as entanglement, ion exchange and complex formation on the surface, in addition to oxidation and reduction reactions. It also discusses the effect of operational factors-such as contact time, pH, adsorbent dosage, temperature and the initial concentration of the contaminant-on removal efficiency.* ***Results****: These studies confirm that green nanoparticles, such as zinc oxide, iron, silver and copper, are characterised by their large surface area , and a high density of active sites, which achieve high efficiencies in the removal of dyes and heavy metals,* ***Novelty:*** *whilst offering significant potential for improving environmental performance compared to conventional chemical methods*

INTRODUCTION

The scientific community has witnessed rapid expansion in industrial activities in which global companies specialise, such as tanning, the textile and paint industries, as well as fertilisers, batteries, pharmaceuticals and the food industry [1]. This expansion leads to the generation of large quantities of industrial effluent containing organic and inorganic pollutants, the characteristics of of this water vary depending on the type of industry, though they often share the presence of heavy metals such as cadmium, lead, nickel, chromium and zinc, in addition to persistent organic compounds and industrial dyes. Conventional water treatment methods, such as filtration, biological treatment and chemical precipitation, are effective in removing some of the pollutants, but they fail to deal with low-concentration pollutants or compounds; this has highlighted the need for advanced technologies capable of removing pollutants at a reasonable cost and with minimal environmental impact. One of the most well-known of these technologies is the adsorption process using nanomaterials; the adsorption process is characterised by being physical and chemical process that relies on the accumulation of pollutant molecules or ions on the surface of a solid material known as the adsorbent [2], [3], [4], [5]. The efficiency of this process increases with an increase in the surface area and the number of active sites on the surface of the adsorbent. Nanoparticles provide us with a very large surface area and due to their small dimensions and very high surface-to-volume ratio,

they possess a higher adsorption capacity than conventional materials such as alumina and carbon. Furthermore, green manufacturing processes for nanoparticles have emerged as a sustainable alternative to chemical methods, utilising plant extracts, microorganisms or algae as sources of reduction and stabilisation, rather than toxic chemical extracts and substances. These extracts contain flavonoids, proteins, phenols and sugars, which in turn act as reducing agents and surface stabilisers; this reduces the use of hazardous materials and improves the environmental compatibility of the particles produced [6], [7], [8], [9], [10].

RESEARCH METHOD

This article presents a narrative, literature-based examination of industrial wastewater contaminants, conventional treatment approaches, adsorption mechanisms, and reported applications of green-synthesized nanoparticles. The discussion draws on the studies cited in the manuscript and compares published removal outcomes and operational considerations. No original laboratory experiments or independent meta-analysis are reported.

Industrial effluent consists of a diverse range of pollutants and can be classified as follows

Firstly: Heavy metals such as zinc, cadmium, nickel, chromium, tin and gold. These pollutants are highly toxic and non-biodegradable

Secondly: Industrial dyes. Examples of such dyes include methylene blue, azo dyes and Congo red, which are primarily produced by the textile, leather and paper industries

Thirdly: Persistent organic compounds. Examples of such compounds include pesticides, phenols, pharmaceutical compounds and surfactants.

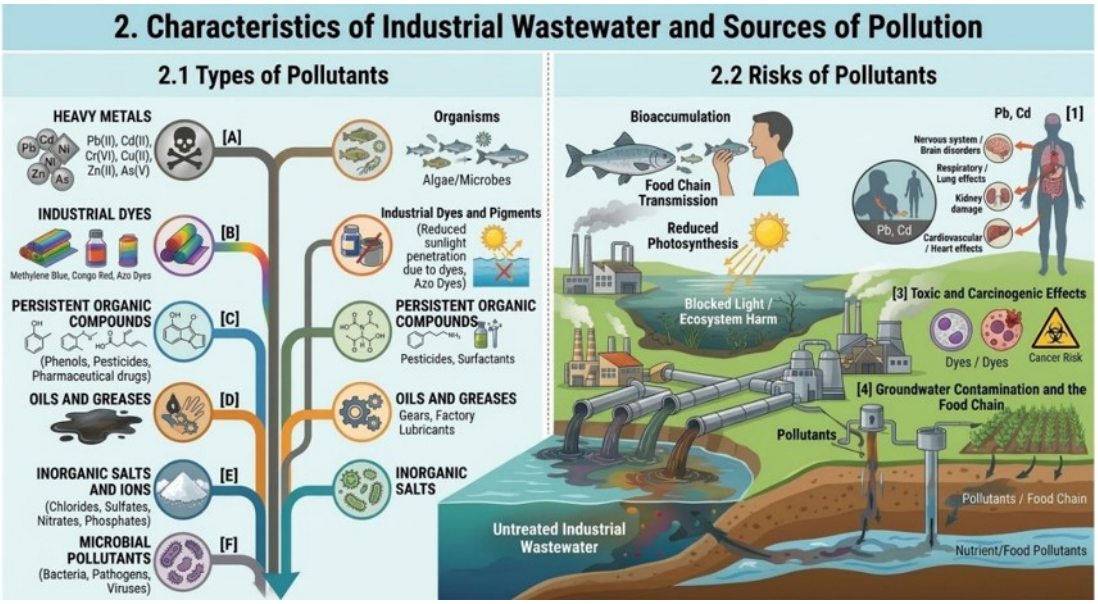
Fourthly: Greases and oils. These substances are produced by the lubricants industry, industrial catering and metal processing.

Fifth: inorganic ions and salts, such as sulphates, nitrates, phosphates and chlorides

Sixth: microbial contaminants; such contaminants are found in certain industrial, food and pharmaceutical effluents [11].

Risks arising from pollutants

The danger posed by heavy metals stems from their bioaccumulation in aquatic organisms and humans, as well as their ability to cause neurological, renal and hepatic disorders. As for pigments, they reduce light penetration in water bodies; furthermore, they hinder photosynthesis and affect the ecological balance, as some dyes and their intermediate compounds possess carcinogenic or cytotoxic properties. The problem is exacerbated when such water is discharged without adequate treatment into lakes, rivers or the soil, as pollutants migrate into groundwater or enter the food chain. Consequently, the effective treatment of industrial effluent has become highly necessary, both for public health and economic reasons [12].



Figures 1. show a diagram illustrating pollutants by type

Conventional Physicochemical Treatment Methods

A number of physical and chemical methods are used in the treatment of industrial effluent, and each of these methods has its own advantages and limitations. Table 1 outlines these methods, along with the principles and advantages on which each is based and Figure 2 illustrates the methods used for the treatment and filtration of industrial effluent [13].

Table 1. Methods used in the treatment of industrial waste water

Method	Principle	Advantages	Limitations
Chemical Precipitation	Converting dissolved pollutants into an insoluble compound	Simple and relatively low-cost	Generates secondary sludge and may not be effective for low concentrations
Ion Exchange	Exchanging pollutant ions with ions on a exchanger resin	High precision and recovery potential	Sensitivity to organic fouling and regeneration cost
Membrane Filtration	Separation of pollutants through selective membranes	High removal efficiency for dissolved pollutants	Membrane clogging/fouling and high energy consumption
Coagulation and Flocculation	Aggregating suspended particles to facilitate their settling	Effective for particles and turbidity	Less effective with dissolved pollutants

Method	Principle	Advantages	Limitations
Adsorption	Accumulation of pollutants on the surface of a solid material	Simple operation, high efficiency, and reusability potential	Requires a suitable adsorbent material and periodic regeneration
Advanced Oxidation	Generating strong free radicals to break down organic pollutants	Effective for persistent compounds	Can be costly and requires specific conditions

Adsorption is one of the most commonly used methods, as this process does not require complex equipment and can be carried out at temperatures close to room temperature; furthermore, natural, synthetic or nuclear adsorbents can be used [14].

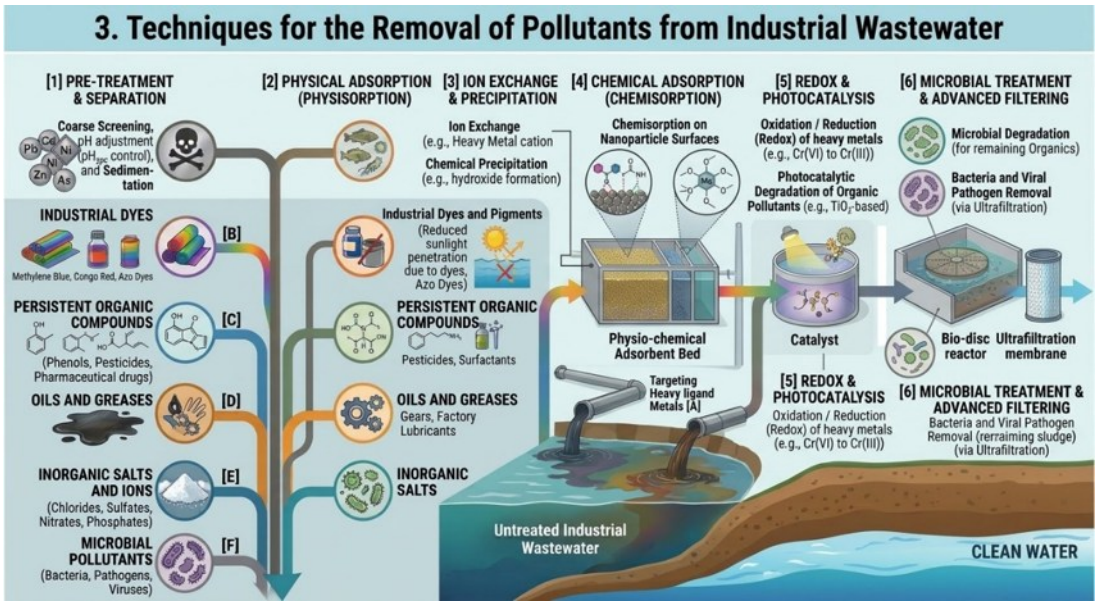


Figure 2. illustrates the methods used for the treatment and filtration of industrial effluent

Adsorption Mechanisms and Physicochemical Principles

The process of adsorption is the accumulation of a substance – known as the adsorbate – on the surface of a solid material known as the adsorbent. When used in water treatment, the adsorbate is usually a metal ion, a dye molecule or an organic compound, whilst the adsorbent can be defined as consisting of particles with nuclei, nanomaterials or porous materials. The adsorption process involves four main stages, namely [15]:

Firstly: the transfer of contaminants from the liquid phase to the boundary layer surrounding the surface

Secondly: diffusion across the liquid film layer at the surface

Thirdly: diffusion occurring within the pores, if present

Fourthly: the actual binding of the contaminant to active sites on the surface

There is another type known as physical adsorption, which occurs as a result of relatively weak attractive forces such as electrostatic interactions, van der Waals forces, hydrophobic interactions and hydrogen bonding. This process has a low adsorption enthalpy and can be easily reversed; it also consists of a layer of m single or multi-layered adsorbent layer. In addition, there is another specific adsorption method known as chemical adsorption, whereby this process relies on the formation of stronger bonds between the surface of the material and the contaminant; these bonds may be ionic, covalent or coordinate bonds, and these materials usually result in the formation a monolayer in which the adsorption temperature may be higher than that observed in the previous physical adsorption method [16], [17], [18], [19], [20]. The final method worth mentioning is known as ion exchange and desorption, whereby the ions of the pollutants present in the solution are replaced by other ions present on the surface of the material. The sorption process, meanwhile, occurs through the binding of metal ions to functional groups such as amino, carboxyl, hydroxyl and thiol groups, whereby these mechanisms play an important role in the removal of heavy metals using nanoparticles coated with polymeric and plant-based compounds [21].

RESULTS AND DISCUSSION

Results

Green Nanoparticles for Industrial Effluent Treatment

Nanoparticles can be characterised by having one dimension typically ranging between one and one hundred nanometres; their small size results in a significant increase in the surface area of the particles used, as well as an increase in the number of active surface atoms, in addition to an improved ability to interact with pollutants. This is considered a key reason why nanoparticles nanomaterials to exhibit higher adsorption capacity and a faster rate of removal compared to conventional granular materials. Furthermore, the properties of these surface materials can be controlled by modifying them with functional groups or by coating them with polymers, carbon-based materials or metal oxides. This allows for the design of selective adsorbents that target specific types of pollutants such as chromium, azo dyes or lead [22].

Applications of Green-Synthesized Nanoparticles

Removal of synthetic dyes

Studies have shown that zinc oxide nanoparticles synthesised using plant extracts or spleen achieved high removal efficiency for methylene blue, with a maximum adsorption capacity of approximately 192 mg/g and a removal efficiency exceeding 98 per cent even when used at low concentrations. It was also concluded that the pseudo-second-order model and the Langmuir model are the best models for describing the process, indicating that monolayer adsorption is dominated by chemical bonding. Furthermore, green-processed nanoparticles can be used to remove dyes from such as Congo red and azo dyes, where electrostatic interactions, π–π interactions and hydrogen

bonding contribute to the binding between the nanoparticle surface and the dye [23], [24], [25], [26], [27].

Removal of heavy metals

The study showed that Fe3O4 particles synthesised using green algae have a high capacity for removing heavy metals—namely molybdenum, cadmium and aluminium—from contaminated water, with removal efficiencies of 97.5 per cent, 81.3 per cent and 75.14 per cent respectively, under pre-determined operating conditions. It was found that the pseudo-second-order model and the Langmuir model were the most suitable for describing the process, and that the adsorption process was exothermic, spontaneous and preferential. Reviews suggest that bio-nanoparticles that achieved removal efficiencies of ranging from 70 per cent to 95 per cent for heavy metals and from 80 per cent to 198 per cent for dyes, whilst demonstrating improved environmental compatibility and reduced environmental toxicity when compared with chemically synthesised particles [28].

Synthesis of Reported Results

The literature discussed above reports methylene blue removal exceeding 98% with an adsorption capacity of approximately 192 mg/g for green-synthesized ZnO nanoparticles, while green-algae-derived Fe3O4 particles were associated with removal efficiencies of 97.5%, 81.3%, and 75.14% for molybdenum, cadmium, and aluminium, respectively [23], [24], [25], [26], [27], [28]. These are results reported by cited studies rather than measurements newly generated for this review. Their comparability is constrained by differences in adsorbent preparation, pollutant identity, initial concentration, pH, contact time, and experimental conditions.

Advantages and Challenges

The advantages and challenges can be summarised in a few points. To begin with, the advantages are as follows:

1. The removal rate is higher than that of conventional materials
2. These materials possess a high surface area and a high adsorption capacity
3. High potential for surface modification to increase selectivity
4. Use of natural materials in green manufacturing, which reduces reliance on harmful substances
5. Reusability, particularly with magnetic particles that can be separated using an external magnet
6. The ability to combine adsorption with photostimulation or oxidation–reduction reactions

As for the challenges, in my view, they can be summarised as follows:

1. The difficulty in separating the particles from the water after use
2- The possibility of magnetic particles agglomerating, thereby reducing their effectiveness
3- The risk of nanotoxicity to aquatic organisms and humans
4- The high cost of large-scale production
5- The need to study the full life cycle in order to assess true sustainability

6- The impact of performance in real-world water systems when compared to laboratory solutions

Recent studies and reviews confirm that most of the evidence remains limited to laboratory studies and preliminary experiments, and that this large-scale application requires solutions to the problems of recovery, reuse, nanotoxicity and cost

Discussion

Following a comprehensive review of this research, a number of recommendations are put forward, which can be summarised as follows:

1. The selection of low-cost, locally sourced plant extracts for the synthesis of nanoparticles
2. The complete characterisation of nanoparticles prior to their application, including their shape, charge, size, surface area and functional groups
3. Study the contact time and the effect of acidity, as well as the dose of the adsorbent, temperature and initial concentration for each type of pollutant.
4. The Freundlich and Langmuir models, as well as kinetic models, can be applied to understand the adsorption process and determine the specific rate-determining steps.
5. Work on developing composite or magnetic secondary particles to facilitate separation and facilitate use
6. Conduct toxicity and environmental impact tests prior to scaling up for field application
7. Conduct a life-cycle assessment to ensure that the environmental benefits of green nanoparticles outweigh their costs and risks

CONCLUSION

Fundamental Finding: The treatment of industrial effluent using nanomaterials manufactured via green methods is considered one of the most promising solutions for treating water pollution caused by heavy metals, persistent organic pollutants and dyes. The success of this technology depends on a thorough understanding of the physicochemical mechanisms of the adsorption process, including electrostatic attraction, ion exchange, hydrogen bonding, adsorption, the formation of surface complexes, as well as oxidation and reduction reactions. **Implication:** Nanoparticles offer significant environmental and technical advantages, such as improved sustainability, reduced use of harmful chemicals, and increased removal efficiency. **Limitation:** However, the transition from the laboratory to practical application requires addressing challenges related to separation, cost, nanotoxicity and reusability, as well as assessing their life cycle. **Future Research:** whilst ensuring research and development, as this technology is expected to play an increasingly important role in industrial wastewater management and the protection of water resources.

REFERENCES

[1] Biosynthesis of zinc oxide nanoparticles with antimicrobial, anticancer, antioxidant and photocatalytic activities by the endophytic Alternaria tenuissima. Journal of Applied Microbiology. 2020;128(6):1634–1646. doi: 10.1111/jam.14581.

[2] Abdo A, Fouda A, Eid A, Fahmy N, Elsayed A, et al, "Green Synthesis of Zinc Oxide Nanoparticles (ZnO-NPs) by Pseudomonas aeruginosa and Their Activity against Pathogenic Microbes and Common House Mosquito, Culex pipiens", Materials. 2021;14:6983. doi: 10.3390/ma14226983.

[3] Abomuti MA, Danish EY, Firoz A, Hasan N, Malik MA, "Green Synthesis of Zinc Oxide Nanoparticles Using Salvia officinalis Leaf Extract and Their Photocatalytic and Antifungal Activities", Biology. 2021;10(11):1075. doi: 10.3390/biology10111075. [DOI] [PMC free article]

[4] Acharya D, Satapathy S, Somu P, Parida UK, Mishra G, "Apoptotic Effect and Anticancer Activity of Biosynthesized Silver Nanoparticles from Marine Algae Chaetomorpha linum Extract Against Human Colon Cancer Cell HCT-116", Biological Trace Element Research. 2021;199(5):1812–1822. doi: 10.1007/s12011-020-02304-7.

[5] Adnan MM, Dalod ARM, Balci MH, Glaum J, Einarsrud MA, "In Situ Synthesis of Hybrid Inorganic–Polymer Nanocomposites", Polymers. 2018;10(10):1129. doi: 10.3390/polym10101129.

[6] Ahmad A, Kamaruddin MA, Abdul Khalil HPS, Yahya EB, Muhammad S, et al, "Recent Advances in Nanocellulose Aerogels for Efficient Heavy Metal and Dye Removal Gels", 9(2023)(5):416. doi: 10.3390/gels9050416.

[7] Aldeen TS, Ahmed Mohamed HE, Maaza M, "ZnO nanoparticles prepared via a green synthesis approach: Physical properties, photocatalytic and antibacterial activity", Journal of Physics and Chemistry of Solids. 2022;160:110313. doi: 10.1016/j.jpcs.2021.110313.

[8] Alhalili Z, "Green synthesis of copper oxide nanoparticles CuO NPs from Eucalyptus Globoulus leaf extract: Adsorption and design of experiments", Arabian Journal of Chemistry. 2022;15(5):103739. doi: 10.1016/j.arabjc.2022.103739.

[9] Ali S, Badar MS, Daniyal Nikkhah A, Fen CS, Nouri A, et al, "Progress in nanomaterial-driven redox reactions for water purification: A critical review", Desalination and Water Treatment. 2024;320:100616. doi: 10.1016/j.dwt.2024.100616.

[10] Aliannezhadi M, Doost Mohamadi F, Jamali M, Shariatmadar Tehrani F, "Ultrasound-assisted green synthesized ZnO nanoparticles with different solution pH for water treatment", Scientific Reports. 2025;15(1):7203. doi: 10.1038/s41598-025-90305-8.

[11] Almutairi FM, El Rabey HA, Alalawy AI, Salama AAM, Tayel AA, et al, "Application of Chitosan/Alginate Nanocomposite Incorporated with Phycosynthesized Iron Nanoparticles for Efficient Remediation of Chromium", Polymers. 2021;13(15):2481. doi: 10.3390/polym13152481.

[12] Aroob S, Carabineiro SAC, Taj MB, Bibi I, Raheel A, et al, "Green Synthesis and Photocatalytic Dye Degradation Activity of CuO Nanoparticles Catalysts", 13(2023)(3):502.

[13] Aswin M, Jeice AR, Rajaram P, "Green synthesis of α-MoO3 nanorods using Tridax procumbens leaf extract for photodegradation and antimicrobial applications against cationic tri-pigments", Journal of Crystal Growth. 2025;666:128229. doi: 10.1016/j.jcrysgro.2025.128229.

[14] Atheena PV, Basawa R, Raval R, "Advancing wastewater treatment: chitin and derivatives for PPCP contaminant mitigation", Polymer Bulletin. 2024;81(16):14307–14336. doi: 10.1007/s00289-024-05429-0.

[15] Baranwal A, Srivastava A, Chandra DP, "A Systematic Study on Phytosynthesized Silver Nanoparticles and Their Antimicrobial Mode of Action", In: Kumar P, Kumar Patra J, Chandra

P, editors. Advances in Microbial Biotechnology. New York: Apple Academic Press; 2018. pp. 538–558.
[16] Chinnathambi A, Alharbi SA, Joshi D, VS, Jhanani GK, et al, "Synthesis of AgNPs from leaf extract of Naringi crenulata and evaluation of its antibacterial activity against multidrug resistant bacteria", Environmental Research. 2023;216:114455. doi: 10.1016/j.envres.2022.114455.
[17] Choudhury P, Mondal P, Majumdar S, Saha S, Sahoo GC, "Preparation of ceramic ultrafiltration membrane using green synthesized CuO nanoparticles for chromium (VI) removal and optimization by response surface methodology", Journal of Cleaner Production. 2018;203:511–520. doi: 10.1016/j.jclepro.2018.08.289 .
[18] CuO nanoparticles for chromium (VI) removal and optimization by response surface methodology. Journal of Cleaner Production. 2018;203:511–520. doi: 10.1016/j.jclepro.2018.08.289.
[19] da Silva Alves DC, Healy B, Pinto LA, de A, Cadaval TRS, Breslin CB, "Recent Developments in Chitosan-Based Adsorbents for the Removal of Pollutants from Aqueous", Environments Molecules. 2021;26(3):594. doi: 10.3390/molecules26030594.
[20] Darroudi M, Ahmad M, Zamiri R, Khorsand Zak A, Abdullah A, et al, "Time-dependent effect in green synthesis of silver nanoparticles", International Journal of Nanomedicine. 2011;2011;6:677–81. doi: 10.2147/IJN.S17669.
[21] Dutta S, Srivastava SK, Gupta B, Gupta AK, "Hollow Polyaniline Microsphere/MnO2/Fe3O4 Nanocomposites in Adsorptive Removal of Toxic Dyes from Contaminated Water", ACS Applied Materials & Interfaces. 2021;13(45):54324–54338. doi: 10.1021/acsami.1c15096.
[22] Farooq N, ur Rehman Z, Khan MI, Iman W, Kanwal I, et al, "A comprehensive review on ceria based materials for environmental-related applications", Inorganic Chemistry Communications. 2024;170:113086. doi: 10.1016/j.inoche.2024.113086.
[23] Gan Y, Li J, Zhang L, Wu B, Huang W, et al, "Potential of titanium coagulants for water and wastewater treatment: Current status and future perspectives", Chemical Engineering Journal. 2021;406:126837. doi: 10.1016/j.cej.2020.126837.
[24] Gebretinsae HG, Tsegay MG, Nuru ZY, "Biosynthesis of nickel oxide (NiO) nanoparticles from cactus plant extract", Materials Today: Proceedings. 2021;36:566–570. doi: 10.1016/j.matpr.2020.05.331.
[25] González-Ballesteros N, Rodríguez-Argüelles MC, Lastra-Valdor M, González-Mediero G, Rey-Cao S, et al, "Synthesis of silver and gold nanoparticles by Sargassum muticum biomolecules and evaluation of their antioxidant activity and antibacterial properties", Journal of Nanostructure in Chemistry. 2020;10(4):317–330. doi: 10.1007/s40097-020-00352-y.
[26] Goutam SP, Saxena G, Singh V, Yadav AK, Bharagava RN, et al, "Green synthesis of TiO2 nanoparticles using leaf extract of Jatropha curcas L", for photocatalytic degradation of tannery wastewater. Chemical Engineering Journal. 2018;336:386–396. doi: 10.1016/j.cej.2017.12.029.
[27] Govindasamy R, Raja V, Singh S, Govindarasu M, Sabura S, et al, "Green Synthesis and Characterization of Cobalt Oxide Nanoparticles Using Psidium guajava Leaves Extracts and Their Photocatalytic and Biological Activities", Molecules. 2022;27(17):5646. doi: 10.3390/molecules27175646.
[28] Gu H, Chen X, Chen F, Zhou X, Parsaee Z, "Ultrasound-assisted biosynthesis of CuO-NPs using brown alga Cystoseira trinodis: Characterization, photocatalytic AOP, DPPH scavenging

and antibacterial investigations", Ultrasonics Sonochemistry. 2018;41:109–119. doi: 10.1016/j.ultsonch.2017.09.006.

*** Khawla S. Mohammed (Corresponding Author)**
Tikrit University, Iraq
Email: Khawla.mohammed122@tu.edu.ig