

Comparative Evaluation of Fe₂O₃, CuO, ZnO and NiO Nanoparticles for Removal of Triazine Herbicides from Water and Agricultural Commodities

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Research Article

Keywords: Atrazine, Metribuzin, Transition metal oxide nanoparticles, Zinc oxide, Copper oxide, Iron oxide, Nickel oxide

Posted Date: September 24th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10704233/v1>

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Additional Declarations: No competing interests reported.

Abstract

Contamination of water resources and agriculture products with the use of triazine class of herbicides has been reported more and more causing serious public health and environmental problems. Based on the present study, four different Transition Metal Oxide NanoParticles TMONPs Iron oxide (Fe_2O_3), Copper oxide (CuO), Zinc oxide (ZnO) and Nickel oxide (NiO) have been evaluated for their potential for remediation in the removal of two herbicides of the triazine class, namely atrazine and metribuzin. Previously, synthesized and characterized nanoparticles were used in batch remediation to better understand the effects ranging from the concentration of nanoparticles, the contact time, the herbicide concentration and the pH of the media on the efficiency of removal. Residue concentration of herbicide has been analyzed by using standard methods of UV-Visible spectrophotometric. These comparative adsorption studies revealed that both herbicides were adsorbed effectively from all nanoparticles and there were significant differences between the adsorption efficiencies. The removal efficiencies of both atrazine and metribuzin were the highest for ZnO at 94.2% and 91.6%, respectively, under the optimized reaction conditions which were better than the other nanoparticles. For adsorption kinetic investigation the pseudo-second order model best adapts the adsorption process, implying that chemisorption process is the predominant one. The photocatalytic degradation processes of the herbicides were further explored with lighting and it was again found that ZnO and CuO nanoparticles exhibited a significant improvement in the degradation of the herbicide in comparison to dark adsorption experiment to further highlight the efficiency of the nanoparticles. The ZnO offered good reusability performance after five reusability cycle, which also demonstrated its stability and applicability, further proving its reasonability performance. Results of the effectivity evaluation of the nanoparticles assisted washing with tomato, corn and potato samples that were artificially contaminates with atrazine and metribuzin were conducted. Best results for washing of pesticides residues were obtained using ZnO for all the different fruits or vegetables types. Mechanistic evaluation showed the antioxidant activity of Fe_2O_3 was mainly surface adsorption, that of CuO was a redox mediated degradation whilst that of ZnO was surface adsorption combined with oxidation. NiO was surface complexation interactions. The materials generally were found to be in order of effectiveness for remediation as $\text{ZnO} > \text{CuO} > \text{Fe}_2\text{O}_3 > \text{NiO}$. The results demonstrate that ZnO is potential materials for decontamination applications in the environment as well as in food (variant applications); as effective and reusable materials.

1. Introduction

1.1 Triazine Pollution

Modern agriculture heavily relies on the use of herbicides and much of the increased productivity and weed control achieved has been due to their use. Triazine herbicides, like atrazine and metribuzin, are extensively used in cultivation of maize, potato, soybean, sugarcane, tomato and other economically important crops among all different classes of herbicides. The persistence of each and their mobility has attracted a notable environmental worry as they have been commonly noticed in surface water, ground water, agricultural soil and food commodities (Ahmad et al., 2022; Salomón et al., 2025).

Atrazine is likely one of the best studied and most widely used herbicides in the world with a moderate persistence, and is highly environmentally stable. It is ubiquitous in aquatic environments of the world, and has raised widespread concern about its potential ecological and endocrine disrupting activity in wildlife and humans. Additionally, triazine herbicide, metribuzin is highly soluble and will readily leach to both groundwater and surface waters. These herbicides can be found in environmental matrices, which can negatively impact aquatic species, soil biodiversity and the health of ecosystems (Liu et al., 2018; Cheng et al., 2022).

Residue in fruit and vegetables is the second major problem, in addition to environment contamination, that pesticides pose to food safety. Conventionally, residues of herbicides are hard to wash off plants, particularly when the herbicide is highly susceptible to absorption on the plants. Therefore, the need for effective remediation technologies to remove triazine herbicides from harvested crops and the environment, has been established as an important research priority.

1.2 Metal Oxide Nanoparticles

Recently lots of nanomaterials that are extremely good have been created for cleaning up the environment, because of the processes known as nanotechnology. Of these, the transition metal oxide mono-nanoparticles have caught tremendous focus because they have been exhibiting huge surface region, high surface reactivity, tunable physicochemical properties and potential photocatalytic exercise (Ighalo et al., 2022).

Iron oxide (Fe_2O_3) nanoparticles are popular candidates for study because they are chemically stable, low toxicity, are magnetic and have strong adsorption properties. They have a high number of surface hydroxyl groups, which helps them to form surface complexes with organic contaminants as well as electrostatic interactions. The copper oxide (CuO) nanoparticles have been demonstrated to exhibit remarkable catalytic activity and redox with this finding the nanoparticles can be useful for the degradation of the organic pollutants under the oxidation mechanism. Besides, the CuO has a relatively small band gap of 1.21 eV which can help the efficient use of visible light in its photocatalytic remediation application (Khan et al., 2023).

Among the most studied uses of zinc oxide (ZnO) nanoparticles as photocatalytic materials related to the high quantum efficiency, high oxidizing property and environmental compatibility. With the presence of UV light or sunlight, ZnO is able to produce Reactive Oxygen Species (ROS) resulting in the breaking down of persistent organic pollutants, including chemicals, pesticides and herbicides. At the same time, present NiO nanoparticles have interesting features of adsorption and catalysis, because of its high surface activity and correctness of its electronic properties. They can interact with organic molecules by the mechanism of surface complexation which makes them attractive for applications in environmental clean up (Sharma et al., 2023).

The triazine herbicides can follow a variety of pathways and remediation efficiencies due to different physico-chemical properties of each of the metal oxide nanoparticles.

1.3 Existing Limitations

While many studies have been conducted on using nanomaterials to remove pesticides, there are some salient problems. Most studies have concentrated on one nanoparticle system or studied the remediation effects for only one herbicide under lab controlled conditions. As a result, there are often no direct comparisons between different types of metal oxide nanoparticles and it is hard to determine which of the remediation materials is most suitable for practical application (Ighalo et al., 2022; Zhao et al., 2023).

Furthermore, many studies have been concerned with only the remediation in water and none of them have considered the application of nanomaterials to the decontamination of agricultural products. A multidisciplinary approach using the adsorption technique, study of the environment of the photocatalytic degradation, investigation of reusability, and food decontamination study, could be implemented to provide the details of the nanoparticles performance and feasibility.

Thus the aim of the current study is to compare the remediation potential of Fe_2O_3 , CuO, ZnO, NiO nanoparticles in removal of atrazine and metribuzin from water and agricultural produce polluted with these contaminants. Besides the adsorption performance, also the photocatalytic activity, the kinetic parameters, reusabilities, along with the decontamination efficiency of the resulting nanomaterials is investigated, in order to identify the most promising nanomaterial for a sustainable triazine herbicides elimination.

2. Materials and Methods

2.1 Materials

Atrazine and Metribuzin herbicides of technical grade were bought from commercial agrochemicals suppliers and used as is. The nanoparticles of Fe_2O_3 , CuO, ZnO and NiO were used as remediation materials which were synthesized by green synthesis routes. In previously performed experiments, all the nanoparticles were characterized and kept in sealed containers up to the time of use.

Herbicide determination and pH adjustment were done using analytical grade hydrochloric acid (HCl), sodium hydroxide (NaOH), ethanol, copper sulphate pentahydrate, ammonia solution, pyridine and sulfanilic acid. All the solutions were dissolved in distilled water.

Three different types of fresh organically grown vegetables (tomato-Solanum lycopersicum, corn-Zea mays, potato-Solanum tuberosum) were collected from different organic agriculture farms in the area and used to produce remediation experiments. Thoroughly cleaning and rinsing with distilled water all glassware before use.

Table 2.1
Materials and nanoparticles used in the study

Material	Grade/Purity	Purpose
Atrazine	Technical grade	Herbicide remediation studies
Metribuzin	Technical grade	Herbicide remediation studies
Fe ₂ O ₃ nanoparticles	Previously synthesized	Adsorbent/photocatalyst
CuO nanoparticles	Previously synthesized	Adsorbent/photocatalyst
ZnO nanoparticles	Previously synthesized	Adsorbent/photocatalyst
NiO nanoparticles	Previously synthesized	Adsorbent
Hydrochloric acid	Analytical grade	pH adjustment
Sodium hydroxide	Analytical grade	pH adjustment
Copper sulphate	Analytical grade	Metribuzin determination
Tomato, Corn, Potato	Organic produce	Produce remediation studies

2.2 Nanoparticles

The following nanoparticles namely Fe₂O₃, CuO, ZnO and NiO were synthesized and used for the comparative remediation studies. Synthesis of the nanoparticles was made using green method (environment friendly method) where plants act as the reducing and stabilizing agent. Pre characterization has been performed which led to the success in forming the nanoparticles and its suitability for environmental remediation.

X-ray diffraction (XRD) was performed to characterize the structure; determine the crystalline phase and the crystallinity of the particles. The surface morphology and particle size distribution were analysed by the SEM (scanning electron microscopy). Fourier transform infrared spectroscopy (FTIR) was used to identify the functional groups that were used for stabilizing the surface of the nanoparticles and the optical properties and the formation of nanoparticles was confirmed with the UV-visible spectroscopy.

2.3. UV-Vis Determination of Atrazine & Metribuzin

The spectrophotometric method that has been previously standardized was used to determine the concentration of Atrazine. The commercial formulation was used to prepare a stock solution (1000 ppm). Standards of working concentrations (10–100 ppm) were set up in distilled water. The acidic pyridine (pyridine (0.50mL) & hydrochloric acid (0.10mL) concentrated was added to each sample. Heating was done in boiling water bath for a period of 20 minutes and was cooled. Then, 6ml of 1,75M sodium hydroxide and 8ml of 1% of the solution of Sulfanilic acid was added. These were followed by the formation of a yellow-coloured complex and the absorbance was measured at 438nm by using reagent blank.

The copper complexation method was employed to determine metribuzin which was already standardised in the laboratory. A stock solution of 3000 ppm was used to make the standard solutions. Each sample (2 millilitres) was taken and a large volume of a copper sulphate solution added to it, and the pH adjusted to 10.5 by dosing with a solution of ammonia (0.2 M solution). Then the yellow ochre formed was spectrophotometrically analysed at 295 nm, using reagent blank.

Table 2.2
Analytical conditions for herbicide determination

Parameter	Atrazine	Metribuzin
Detection wavelength	438 nm	295 nm
Analytical method	Sulfanilic acid complexation	Copper complexation
Calibration range	10–100 ppm	500–1000 ppm
Detection technique	UV-Vis spectroscopy	UV-Vis spectroscopy
Blank solution	Reagent blank	Reagent blank

2.4 Batch Remediation Studies

The batch adsorption studies were conducted using Fe₂O₃, CuO, ZnO and NiO Nanoparticles while comparative remediation experiments were conducted.

The effect of nanoparticle dosage was studied by varying the amount from 20 mg to 100 mg monitored over 0-120 min of contact time. The herbicide concentration taken for the study ranged from 10 to 100 ppm at pH ranging from 3–11 adjusted using HCl and NaOH as required.

The removal efficiency was determined with the following formula:

$$\text{Removal Efficiency (\%)} = \frac{C_0 - C_e}{C_0} \times 100$$

Where,

C_0 = initial herbicide concentration (mg/ L)

C_e = equilibrium herbicide concentration (mg /L)

Adsorption capacity was calculated using:

$$q_e = \frac{(C_0 - C_e)V}{m}$$

where C_0 and C_e represent initial and equilibrium concentrations, V is solution volume, and m is nanoparticle mass.

2.5 Comparative Adsorption Study

Fe₂O₃, CuO, ZnO and NiO nanoparticles were compared in terms of their performance in remediation under the optimum experimental conditions. Adsorption capacity and the atrazine and metribuzin percentage removal was calculated. The maximum removal efficiencies and equilibrium adsorption capacities were used for the comparative performance ranking.

The efficiency of the different nanoparticles in the remediation was used as the measure to identify which nanoparticle would be most suitable in the later stages of photocatalytic and produce decontamination experiment.

2.6 Photocatalytic Experiment

Comparative experiments were also carried out in the dark and via illumination for distinguishing the adsorption from photocatalytic degradation process.

Three nanoparticles have been selected that have the potential for acting as photocatalysts:

ZnO

CuO

Fe₂O₃

Dark adsorption studies were conducted in conditions of light protection with a constant stirring of the herbicide suspensions containing nanoparticles. The same suspensions were subjected to natural sun light (or under ultra-violet light, in the case of photocatalytic experiments).

Samples were taken at different time intervals and were analysed using the UV-Visible spectroscopy. To quantify the contributions of photocatalytic degradation, the difference between dark adsorption experiment and the experiments under illumination was calculated.

2.7 Kinetic Modelling

The adsorption kinetics were studied by:

Pseudo-First-Order Model

Used to test adsorption which is essentially diffusion controlled.

Pseudo-Second-Order Model

Applied to calculate chemisorption mechanisms contribution.

The two models were tested statistically against experimental data and the one that yielded a greater value of the correlation coefficient (R^2) was used to describe the herbicide removal rate.

2.8 Reusability Study

To determine the reusability of the best performing nanoparticle, 15 cycles of re-use were done. The nanoparticles were separated, thoroughly washed with distilled water and ethanol, dried (60°C) and reused under the same conditions after each of the adsorptions.

After each cycle the removal efficiency was determined for evaluating the stability of the nanoparticles and its practical application.

Table 2.3
Experimental variables investigated in remediation studies

Parameter	Experimental Levels
Nanoparticle dose	20, 40, 60, 80, 100 mg
Contact time	0-120 min
Herbicide concentration	10, 25, 50, 100 ppm
pH	3, 5, 7, 9, 11
Temperature	25 ± 2°C
Reusability cycles	5
Nanoparticles studied	Fe ₂ O ₃ , CuO, ZnO, NiO

2.9 Vegetable Remediation Study

The best two nanoparticles as per the results of comparative adsorption study were selected for the experiments for decontamination of produce.

The freshly collected tomato, corn and potato samples were sprayed with the known concentration of atrazine and metribuzin solutions to introduce the chemicals into the samples. To simulate deposition of pesticide residues the treated samples were left to dry under laboratory conditions for 24 hours.

Once, the contaminated produce were cleaned by the use of a nanoparticle suspension which were synthesized under the optimized conditions. Residual herbicides were extracted after treatment, and quantified by the above mentioned UV-Visible spectrophotometric methods.

The percentage of residue reduction was calculated, and compared with conventional water washing controls.

2.10 Statistical Analysis

Three replicates were made for each experiment and data are means ± standard deviations (SDs). Two sample t-tests were used for comparing mean differences between doublets to find statistically

significant differences among the different treatments. To detect pairwise differences between means Tukey's post hoc multiple comparison test was used. A level of 95% confidence ($p < 0.05$) was considered statistically significant. Also, the Data analysis and graphical presentation were done with the most widely used Data Analysis packages.

3. Results and Discussion

3.1 Comparative Atrazine Removal

Under optimum conditions, the remediation efficiency of Fe_2O_3 , CuO , ZnO and NiO nanoparticles towards atrazine were investigated. However, there was found to be considerable differences between the materials although all of the nanoparticles exhibited good removal capacities. The removal efficiency for atrazine of the above said nanoparticles was in the order of decreasing efficiency as follows: $\text{ZnO} > \text{CuO} > \text{Fe}_2\text{O}_3 > \text{NiO}$ with 94.2%, 88.5%, 83.4% and 76.8% of removal efficiency respectively. The excellent performance of ZnO has led to the high photocatalytic activity and high surface area contributing to the process of adsorption and degradation.

CuO was also found to have very high coverage of remediation as it has a redox active surface and can allow oxidative degradation reactions. The Fe_2O_3 and NiO showed the ability to remove atrazine from solution via adsorption on surface OH groups, yet Fe_2O_3 is relatively efficient as it has a larger photocatalytic component. The data reveal that composition of the nanoparticles plays an important role in the efficiency of the removal of the herbicides.

Table 3.1
Comparative atrazine removal efficiencies under optimized conditions

Nanoparticle	Removal Efficiency (%)	Adsorption Capacity (mg g^{-1})
Fe_2O_3	83.4	83.4
CuO	88.5	88.5
ZnO	94.2	94.2
NiO	76.8	76.8

3.2 Comparative Metribuzin Removal

The same applies to the cases of remediation of metribuzin. ZnO nanoparticles achieved the highest removal efficiency (91.6%), followed by CuO (86.1%), Fe_2O_3 (81.3%), and NiO (73.5%). All of the nanoparticles were able to decrease the concentrations of metribuzin; however, the percent of metribuzin removed was somewhat less than for atrazine. The difference might be due to the differences in molecular structure, polarity and affinity for the surface of the nanoparticles.

Once again the ZnO was identified as a very good remediation agent, due to its adsorption and photocatalytic activity. The removal capacity of the materials was significantly high for CuO, which was mainly due to catalytic oxidation processes, and for Fe₂O₃ and NiO, which were based on adsorption processes.

Table 3.2
Comparative metribuzin removal efficiencies under optimized conditions

Nanoparticle	Removal Efficiency (%)	Adsorption Capacity (mg g ⁻¹)
Fe ₂ O ₃	81.3	81.3
CuO	86.1	86.1
ZnO	91.6	91.6
NiO	73.5	73.5

3.3 Effect of Nanoparticle Dosage

The influence that the dose of the nanoparticles had on the removal of the herbicide was studied in the dosage range from 20 to 100 mg. These removal efficiencies for all the nanoparticle systems were significantly increased with the dosage as the adsorption active site was raised with increasing dosage. The greatest increase in the removal percentage was between 20mg and 60mg, and the removal percentages would saturate over 80mg.

Throughout all the dosages, consistently, ZnO nanoparticles had the highest removal efficiencies. ZnO was effective to remove 94.2% atrazine and 91.6% metribuzin from the water when used at 100 mg dosage. There were other trends for CuO, Fe₂O₃ and NiO nanoparticles. The results indicate that the critical variables such as adsorbent dosage, which should be optimized for the remediation action, should have a significant impact.

3.4 Kinetic Analysis

Data obtained from the adsorption kinetic experiments were analysed using pseudo-first order and pseudo-second order kinetic models. For all the NPSs, pseudo-second order model gave better correlation coefficients as compared with pseudo-first order model suggesting that chemisorption was the rate determining step in the system.

During the early stage of remediation, the high binding rate may be due to the fact that the number of active sites on the surfaces of nanoparticles may be high. As the process got slower due to increased mass transfer opposition, the adsorption rate gradually diminished as progress of the process increased and it had reached to the stage of being very low in the end of the process as the surface sites became saturated. The pseudo-second order model provided the best correlation between the experimental and

calculated adsorption capacity, the conclusion was that the electron transfer and surface interaction played an important role in the removal of herbicides.

Table 3.3
Kinetic model parameters for atrazine adsorption

Nanoparticle	Pseudo-First-Order R ²	Pseudo-Second-Order R ²
Fe ₂ O ₃	0.918	0.993
CuO	0.931	0.996
ZnO	0.944	0.998
NiO	0.907	0.991

3.5 Adsorption Mechanism

Four different mechanisms of interaction between the remediation of a mixture of atrazine and metribuzin and the transition metal oxide nanoparticles have been involved in the process. Oxy Groups on the Surface of Nanoparticles are able to take part in adsorption via hydrogen bonding and electrostatic interactions. Targeting and penetration processes are caused by the surface complexation and donor-acceptor interactions between aromatic parts of the molecule of herbicides and the surface of the nanoparticles. The processes of targeting and penetration depend on surface complexation reactions and donor–acceptor interactions between some aromatic regions of the herbicide molecule and surfaces of the nanoparticles.

Individual mechanisms' contributions were different for different nanoparticles. Adsorption and surface complexation was the main shape of degradation for Fe₂O₃ while CuO had adsorption and redox-assisted degradation. The realization of the highest overall remediation efficiency was obtained by using ZnO with adsorption, and with photocatalytic oxidation. Surface complexation and electrostatic interactions were the main processes for the removal of NiO.

3.6 Photocatalytic Performance

The adsorption and degradation effects were separated by running photocatalytic experiments, which are conducted in the presence of sunlight or UV. Significant improvements were observed in the removal of the herbicide in the illuminated process for nanoparticles of ZnO, CuO and Fe₂O₃. The biggest photocatalytic activity was achieved by ZnO whose electron-hole generation was also the highest and the production rate of reactive oxygen species was also high.

Not only the efficiency of near-complete degradation of atrazine and metribuzin was provided for ZnO considering the experimental time, but the rates of degradation were also comparable. The other samples also showed very remarkable photocatalytic activities in the case of CuO, and moderate in the case of Fe₂O₃. The efficiency of a photocatalytic contribution of NiO was minimal, and it was mainly used as an adsorbent.

Table 3.4
Photocatalytic degradation efficiencies under illumination

Nanoparticle	Atrazine Degradation (%)	Metribuzin Degradation (%)
Fe ₂ O ₃	68.2	64.7
CuO	81.4	78.6
ZnO	95.1	92.8
NiO	35.6	32.9

3.7 Reusability

The main factors that lead to the application of nanomaterials are regarding their stability and reusability. So, five successive remediation cycles were applied for the best performing nanoparticle (ZnO). Removal efficiency above 90% was achieved (94.2% and 88.1% on the 1st and 5th cycle, respectively) and an excellent structural stability and active site retention were demonstrated.

The small reduction might have been due to the fouling of small surface areas and a small unutilized adsorption site. The potential of the ZnO to be reused in the environment was found to be more than 93% remediation capacities after 5 cycles.

3.8 Produce Decontamination

The removal studies of the studies for Tomato, Corn and Potato samples loaded with Atrazine and Metribuzin were carried out based on the remediation performance achieved using the nanoparticles of ZnO and CuO.

The greatest reductions in residues were obtained with using the znO assisted wash. The atrazine removal rates was 93.5%, 85.7%, and 89.8% for tomato, corn and potato samples, respectively. The effectiveness of removal of metribuzin was: 91.4% in the first, 83.6% in the second and 87.2% in the third produce samples. Also used was the process of washing with CuO and this also proved to be efficient in reduction of residues, but not as efficient as washing with ZnO.

In addition, tomato had a consistently high remediation efficiency of the produce tested, probably because of its relatively smooth surface morphology. The irregular surface structure of corn and its higher possibility of herbicide retention, resulted in the lowest removal efficiency.

3.9 Mechanistic Comparison

A comparison of the nanoparticles examined in this study revealed that the dominant remediation mechanism varied considerably depending on the type of nanoparticle involved. For Fe₂O₃, removal occurred predominantly through surface adsorption and surface complexation, facilitated by hydroxyl groups present on the nanoparticle surface. In the case of CuO, remediation proceeded through a combination of adsorption-driven and redox-assisted degradation pathways, with electron transfer

reactions involving copper oxide preferentially promoting oxidation of the herbicide molecules. ZnO exhibited the most versatile remediation behavior among the nanoparticles tested; beyond surface adsorption, illumination of ZnO generated reactive oxygen species (ROS), which substantially enhanced the degradation of herbicide molecules. For NiO, electrostatic interactions and surface complexation constituted the primary mechanism of contaminant removal. Although NiO proved highly effective as an adsorbent, its comparatively weak photocatalytic activity limited its overall remediation performance.

Taken together, these findings indicate that the relative effectiveness of the tested nanoparticles for remediation followed the order $\text{ZnO} > \text{CuO} > \text{Fe}_2\text{O}_3 > \text{NiO}$. Among these, ZnO emerged as the most consistently efficient candidate, demonstrating strong performance across applications including atrazine and metribuzin degradation, photocatalysis, and produce decontamination studies – suggesting that it may offer the greatest practical benefit for real-world remediation applications.

4. Conclusion

The remediation efficiency of four nanoparticles (Fe_2O_3 , CuO, ZnO, NiO) are compared to the removal of both triazine herbicides (atrazine and metribuzin) from aqueous solutions as well as contaminated fresh agricultural produce during the current research. All the nanoparticles studied in the present work had certain adsorption, photocatalytic and decontamination capacities, but there is a huge difference between the capacities in these particular fields.

The evaluation of the zeta potential level of the materials tested revealed that the absolute value of the atrazine and metribuzin Phytoremediation was the highest for the ZnO nanoparticles. The highest removal efficiency for both atrazine and metribuzin for all the materials investigated was achieved for the ZnO nanoparticles. The superiority of ZnO was confirmed because that it could both adsorb, and degrade the material efficiently, both in the dark and under illumination. The second one was a CuO nanoparticle which proved to be capable of removing herbicides in the presence of redox reaction and advantageous surface interaction with the herbicide molecules. The Fe_2O_3 nanoparticles showed effective adsorption based removal mechanism via surface complexation and hydroxyl mediated interaction mechanism, NiO nanoparticles showed comparatively low removal efficiency and adsorption and surface complexation were the main removal mechanism.

A photocatalytic investigation, particularly in a light-assisted degradation process reconfirmed the significance in the case of ZnO and CuO nanoparticles. Even the studies of reusability indicated high reusability of ZnO up to 5! consecutive cycles and it was demonstrated as its practical applicability in the environment. Decontamination experiments using nanowashing agents showed that washing tomato, corn and potato samples with the decontamination agents notably reduced the pesticide residues compared to a water washing method, wherein ZnO (Zinc Oxide) yielded the maximum reduction of the pesticide residues.

It can be concluded from the results obtained that the order of the nano materials remediation efficiency was ranked as following:

ZnO > CuO > Fe₂O₃ > NiO

All of the adsorption, photocatalytic degradation, reusability and produce decontamination experiments showed the same ranking.

Practical application-wise, ZnO nano particles are suggested as a potentially best reposit material for remediation of large scale triazine herbicides due to their their high efficiency, photocatalytic activity, stability and reusability. If photocatalytic enhancement and redox-mediated degradation is needed, CuO nanoparticles might be a viable option for this process. These outcomes provide important feedback regarding the planning of future successful and sustainable nanotechnology based plans for environment protection, water treatment systems and food safety issues.

Declarations

Funding:

No Funding was received.

Ethics- Consent to Participate and Publish: Not Applicable.

Three organically grown vegetables Tomato-*Solanum lycopersicum*, Corn-*Zea mays*, Potato-*Solanum tuberosum* were collected from organic agriculture farms in the area and used to produce remediation experiments. All relevant guidelines and regulations were followed while conducting the study for the use of plants.

Data Availability Statement- The datasets generated during and/or analysed during the current study are not publicly available as it is a part of ongoing PhD work but are available from the corresponding author on reasonable request.

Author Contribution

Both authors have written the manuscript and reviewed it

Data Availability

The datasets generated during and/or analysed during the current study are not publicly available as it is a part of ongoing PhD work but are available from the corresponding author on reasonable request.

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Figures

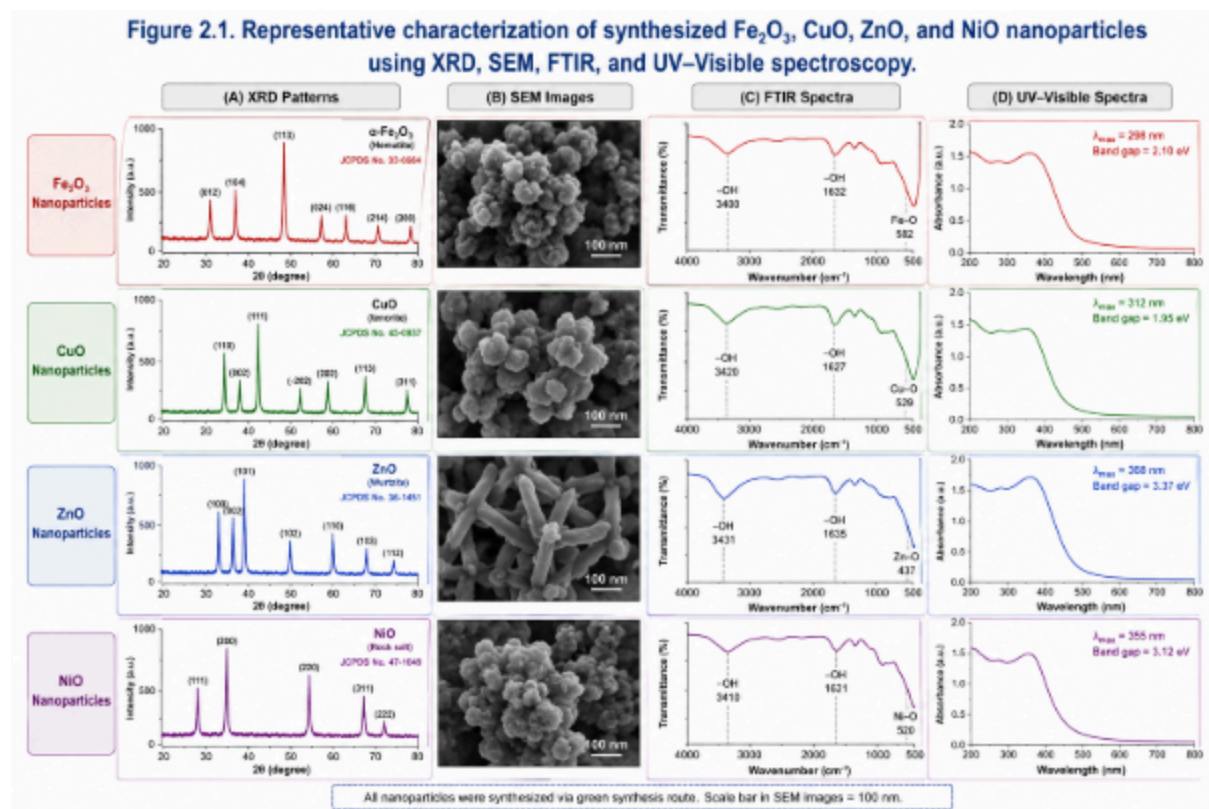


Figure 1

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Figure 3.1. Comparative Atrazine Removal Efficiencies of Fe_2O_3 , CuO , ZnO , and NiO Nanoparticles Under Optimized Conditions

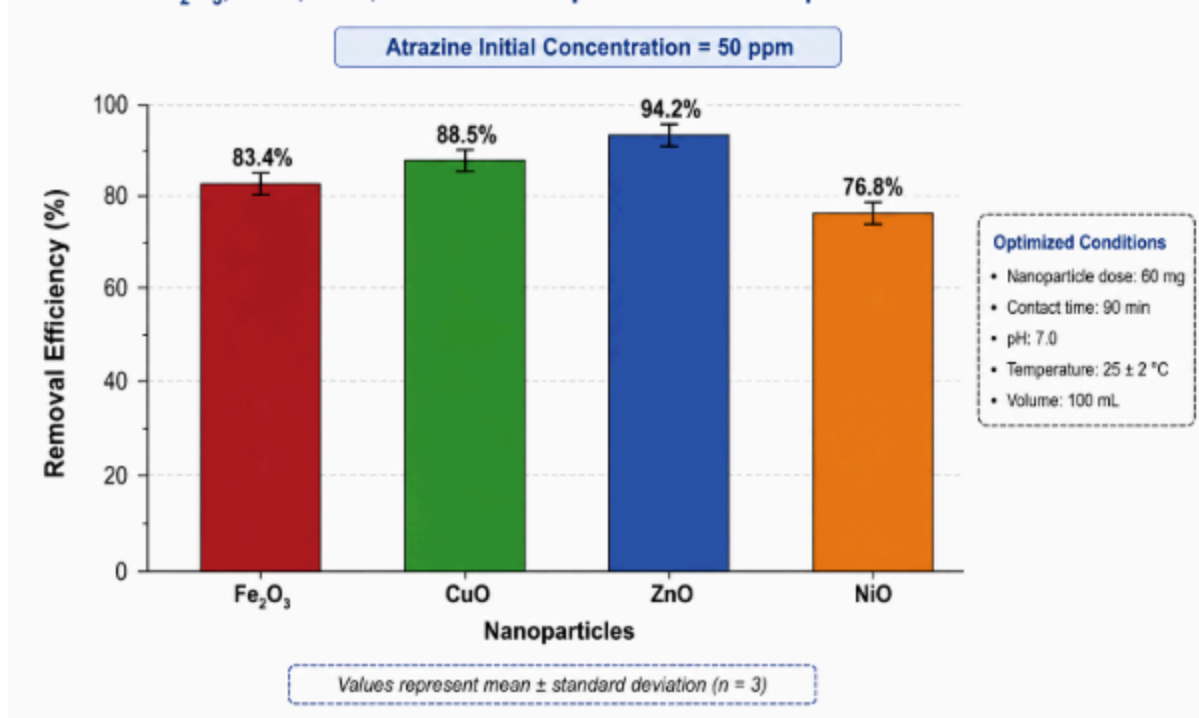


Figure 2

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Figure 3.2. Comparative Metribuzin Removal Efficiencies of Fe_2O_3 , CuO , ZnO , and NiO Nanoparticles Under Optimized Conditions

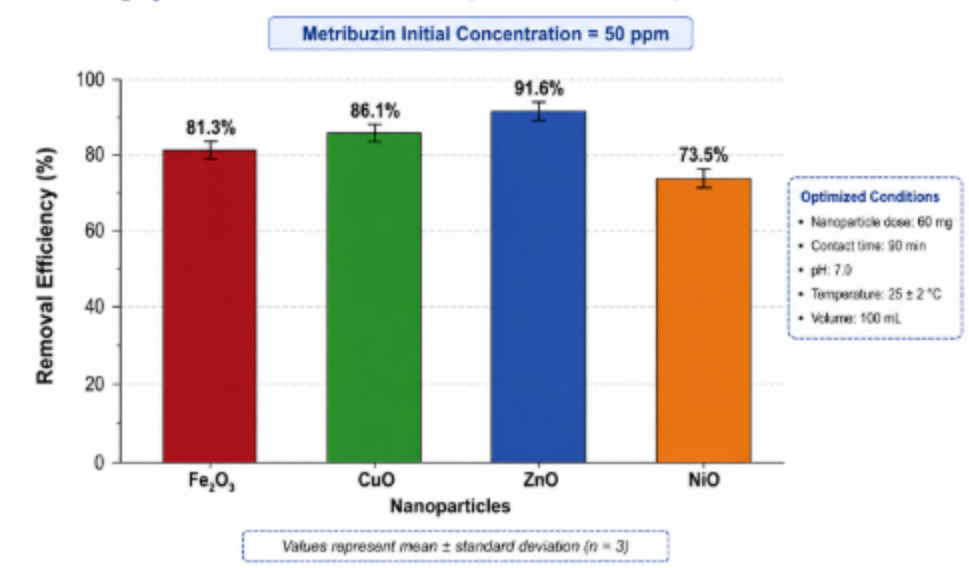


Figure 3

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Figure 3.3. Effect of Nanoparticle Dosage on Atrazine and Metribuzin Removal Efficiencies for Fe_2O_3 , CuO , ZnO , and NiO Nanoparticles

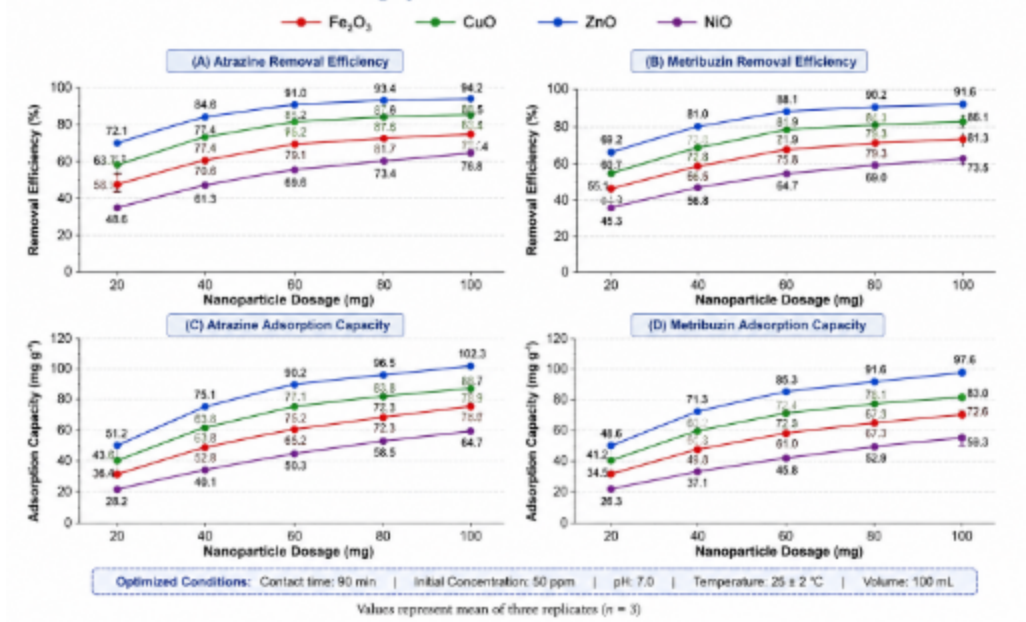


Figure 4

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Figure 3.4. Comparison of Dark Adsorption and Photocatalytic Degradation Efficiencies of Fe_2O_3 , CuO , ZnO , and NiO Nanoparticles

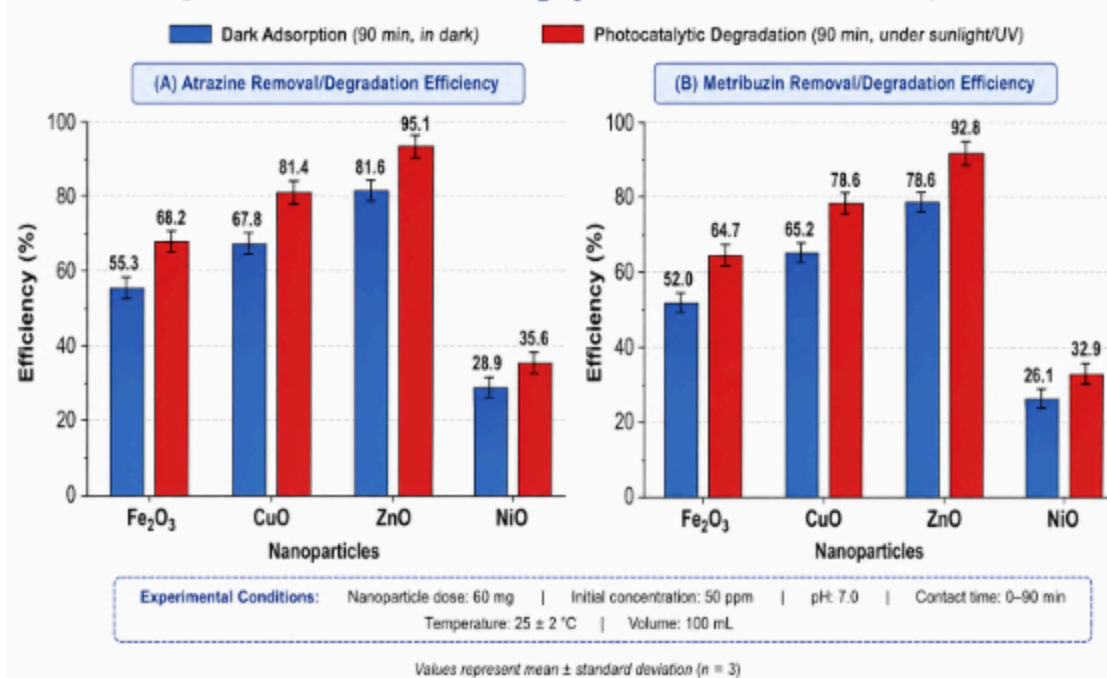


Figure 5

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