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SUSTAINABLE RESTORATION: ASSESSING GREEN-SYNTHESIZED NANOPARTICLES FOR MITIGATING SOIL AND WATER CONTAMINATION FROM MARBLE MINING

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ABSTRACT:

Marble mining is a major contributor to environmental pollution, causing severe contamination of soil and water through the release of heavy metals, suspended particles and alkaline residues. Traditional remediation techniques are costly and involve risk of secondary contamination, requiring environmentally friendly alternatives. This study investigates the potential of green synthesized metal nanoparticles (NPs) as a sustainable solution to mitigate soil and water pollution in regions affected by marble mining. Biogenic metal nanoparticles, produced using plant extracts and microbial agents, present a promising solution because of their high surface area, catalytic properties, and minimal environmental footprint. The study assesses the efficiency of green nanoparticles in adsorbing heavy metals, stabilizing soil pH, and degrading pollutants through laboratory and field experiments. Advanced analytical techniques like SEM, XRD, and FTIR, are utilized to examine the nanoparticles structural and functional attributes. Additionally, the environmental advantages of nanoparticle-based remediation are evaluated, with a focus on restoring soil fertility and improving water quality. The findings underscore the potential of green nanotechnology as a cost-effective and environmentally sustainable strategy to mitigate the adverse effects of marble mining. The findings highlight the potential of green remediation methods and lays the groundwork for their broader application in mining-impacted regions.

KEYWORDS:

GREEN SYNTHESIS, NANOPARTICLES, MARBLE MINING, SOIL POLLUTION, WATER POLLUTION, HEAVY METAL ADSORPTION.

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1. INTRODUCTION

The marble mining industry is a cornerstone of economic development, providing essential materials for construction, decoration, and various industrial applications. However, the environmental implications of this industry are significant, particularly concerning soil and water contamination [1]. Marble mining and processing generates large amounts of waste, including particulates, heavy metals and chemical residues [2],[3], which seep into the surrounding ecosystem. These pollutants reduce soil fertility, alter microbial communities and impair water quality, posing serious threats to both ecological balance and human health. [4],[5],[6].

A critical environmental issue linked to marble mining is the release of toxic load metals such as lead (Pb), chromium (Cr), cadmium (Cd), and nickel (Ni), which originate from mining processes and associated industrial activities [7]. When these toxic elements accumulate in soil and water bodies, they pose long-term ecological and health hazards, leading to bioaccumulation in food chains and groundwater contamination [8],[9]. Moreover, excessive accumulation of marble dust alters soilpH, reducing soil permeability and inhibiting plant growth, further exacerbating land degradation[10],[11].

Traditional remediation techniques, such as chemical treatment and physical removal, are often costly, labour-intensive and can introduce secondary pollutants. Therefore, there is growing interest in applying nanotechnology to sustainable remediation[12]. Among new approaches, the use of green metal nanoparticles (NPs) is gaining popularity due to their cost-effectiveness, environmental friendliness, and high pollutant removal efficiency[13],[14]. Green synthesis uses plant extracts, microorganisms, or biowaste to produce nanoparticles, reducing the need for toxic chemicals and promoting environmental sustainability [15],[16].

Metal-based nanoparticles such as silver (Ag), iron (Fe), and zinc oxide (ZnO) have shown remarkable potential in remediating contaminated sitesas these nanoparticles exhibit strong adsorption properties, catalyze degradation reactions, and help sequester heavy metals from soil and water systems [17],[18]. Furthermore, integrating green chemistry principles into the synthesis of nanoparticles not only improves their biocompatibility but also aligns with the global effort to develop cleaner technologies for environmental remediation [19].

This study aims to evaluate the extent of soil and water contamination caused by marble mining activities and evaluate the effectiveness of synthetic green metal nanoparticles as a remediation strategy[20]. By combining environmental monitoring with an innovative nanotechnology-based approach, this research aims to propose sustainable methods to mitigate the environmental impact of marble mining[21].

FIGURE1: STUDY AREA.

GREEN SYNTHESIZED METAL NANOPARTICLE: Green synthesized metal nanoparticles (NPs) is a sustainable, cost-effective, and eco-friendly approach to producing nanoparticles from biological sources such as, plant extracts, fungi, bacteria, algae, etc. Unlike traditional chemical synthesis and physical synthesis, which often rely on hamful solvents and hazardous reagents, green synthesis uses natural reducing agents and stabilizers, making it more environmentally friendly[22],[23].

STUDYAREA SAMPLING STRATEGY:

SELECTION OF STUDY SITES: Contaminated soil and water samples to be collected from marble mining sites in Rajsamand district of Rajasthan. The study focuses on the sustainable restoration of areas affected by marble mining in Rajsamand district, specifically Piplantri, Morchana, and the RK Marble site. Below is an overview of each location, including their geographical coordinates:

1. PIPLANTRI VILLAGE

Approximately 25.11262°N latitude and 73.7885°E longitude, Piplantri is a special village that does something really cool for the environment. Since 2006, whenever a baby girl is born, the people in the village plant 111 trees. Because of this, plantation rapidly increased to more than 350,000 trees like neem, sheesham, mango, and amla. This helps the ground hold more water and makes the plants and animals in the area happy and healthy.

2. MORCHANA VILLAGE

Approximately 25.10332°N latitude and 73.86195°E longitude, Morchana is a village that is about 5.5 kilometers away from a place called Rajsamand. It is quite big, covering an area of 193.91 hectares, and has 1,699 people living there. The village has been affected by marble mining, which means that digging for marble has changed the soil and water in the area.

3. RK MARBLE PVT. LTD.

It works in the Rajsamand region, with objects near Kankroli in the Rajsamand region. As a well -known business for marble and treatment, RK Marble operations \ Extraction and conversion activities raise concerns about soil degradation and water contamination in surrounding areas.

SAMPLING METHODOLOGY:

- Soil samples will be collected at various depths (0-10 cm, 10-20 cm and 20-30 cm) using an auger.
- Water samples will be collected in sterile bottles from nearby groundwater sources and surface water bodies.

MATERIALSANDMETHODS:-

RESEARCH DESIGN: This study employs a mixed-methods approach, integrating both qualitative and quantitative methods to evaluate soil and water contamination due to marble mining and the effectiveness of green nanoparticle-based remediation techniques. A comparative experimental design will be used to assess the remediation efficiency of green nanoparticles against conventional methods.

PIPLANTRI

- pH (7.60 – 8.81): Slightly alkaline; supports moderate crop growth.
- Electrical Conductivity (0.50 – 0.73 dS/m): Low to
- moderate salinity; acceptable for most crops.
- Organic Carbon (0.52 – 0.72%): Good organic content; promotes soil fertility.
- Available Nitrogen (140.01 – 252.68 kg/ha): Moderate to high nitrogen; beneficial for vegetative growth.
- Phosphorus (15.11 – 54.13 kg/ha): High variability; good for root development and flowering.
- Potassium (125.31 – 630.15 kg/ha): Wide range; can support fruiting and disease resistance.
- Sodium (0.52 – 0.97 meq%): Higher end sodium; may need monitoring to prevent soil degradation.

SUMMARY: Piplantri soil is fairly fertile with balanced nutrients, though slightly alkaline and with a wide potassium range, which may need management

TABLE 1: EVALUATION OF PHYSICOCHEMICAL PROPERTIES IN SOIL SAMPLES

Parameter	Piplantri	Morchana	R.K. Marbles
pH	7.60 - 8.81	7.50 - 8.70	7.40 - 8.60
Electrical Conductivity	0.50 - 0.73 dS/m	0.45 - 0.70 dS/m	0.40 - 0.68 dS/m
Organic Carbon	0.52 - 0.72%	0.50 - 0.70%	0.48 - 0.68%
Available Nitrogen	140.01 - 252.68 kg/ha	135.00 - 250.00 kg/ha	130.00 - 245.00 kg/ha
Phosphorus	15.11 - 54.13 kg/ha	14.00 - 52.00 kg/ha	13.00 - 50.00 kg/ha
Potassium	125.31 - 630.15 kg/ha	120.00 - 620.00 kg/ha	115.00 - 610.00 kg/ha
Sodium	0.52 - 0.97 meq%	0.50 - 0.95 meq%	0.48 - 0.93 meq%

MORCHANA

- pH (7.50 – 8.70): Slightly alkaline, similar to Piplantri.
- Electrical Conductivity (0.45 – 0.70 dS/m): Low salinity, crop-friendly.
- Organic Carbon (0.50 – 0.70%): Adequate organic matter for soil health.
- Available Nitrogen (135.00 – 250.00 kg/ha): Slightly less than Piplantri but still good.
- Phosphorus (14.00 – 52.00 kg/ha): Nutrient-rich; supports plant maturity.
- Potassium (120.00 – 620.00 kg/ha): Similar to Piplantri with wide range.

Sodium (0.50 – 0.95 meq%): Also slightly high, though manageable.

SUMMARY: Morchana's soil is also productive and stable, with comparable nutrient levels to Piplantri. Slight sodium buildup might require attention.

R.K. MARBLES

- pH (7.40 – 8.60): Slightly less alkaline than others; still suitable for many crops.
- Electrical Conductivity (0.40 – 0.68 dS/m): Lowest EC; very low salinity – favorable.
- Organic Carbon (0.48 – 0.68%): Adequate, though reduced.
- Available Nitrogen (130.00 – 245.00 kg/ha): Slightly lower than the other two; may benefit from nitrogen enrichment.
- Phosphorus (13.00 – 50.00 kg/ha): Slightly lower range, still useful.
- Potassium (115.00 – 610.00 kg/ha): Lower minimum value, but adequate overall.
- Sodium (0.48 – 0.93 meq%): Lowest sodium content; better for long-term soil structure.

SUMMARY: R.K. Marbles' soil is relatively less fertile than the others but has the lowest salinity and sodium levels, which is a positive for sustainability and long-term crop health.

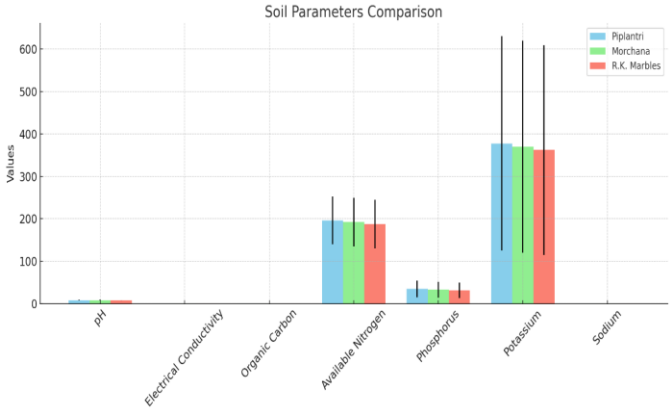


FIGURE 2: COMPARING SOIL PARAMETERS ACROSS PIPLANTRI, MORCHANA, AND R.K. MARBLES.

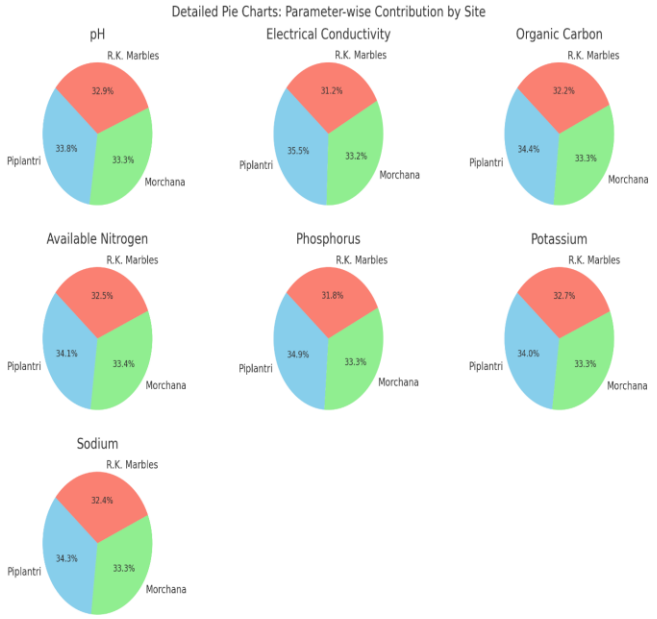


FIGURE 3: PIE CHARTS SHOW THE PARAMETER-WISE AVERAGE CONTRIBUTION OF EACH SITE—PIPLANTRI, MORCHANA, AND R.K. MARBLES.

Characterization of Contamination:

The following tests are performed to determine the level and type of contamination-

Physicochemical Analysis:

Soil: pH, organic matter, electrical conductivity, particle size distribution.

Water: pH, turbidity,oxygen, totals dissolved solids, and heavy metal concentrations.

Heavy Metal Analysis:

Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Atomic Absorption Spectroscopy (AAS) are used to quantitatively determine heavy metals (Pb, Cd, Cr, Ni, etc.)

X-ray Fluorescence Spectroscopy (XRF) is used for elemental analysis.

Green Nanoparticle Synthesis and Characterization:

Green nanoparticles (e.g. iron oxide, zinc oxide, silver nanoparticles) can be synthesized through plant extracts such as Murraya koenigii, Azadirachta indica.

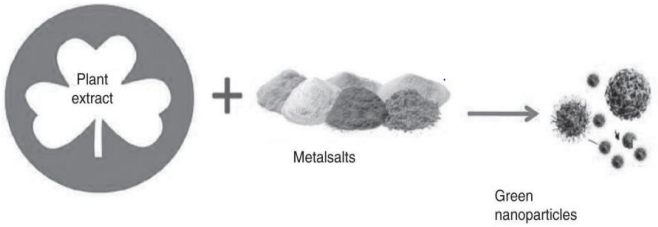
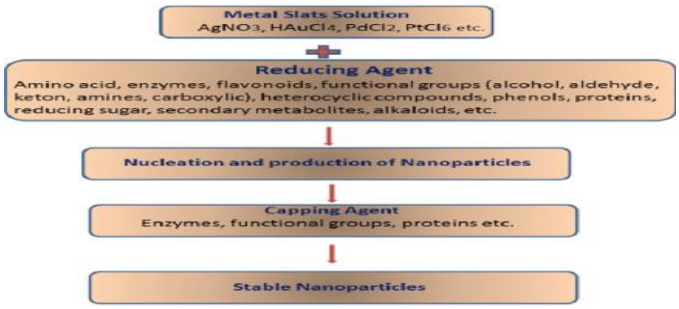


FIGURE 3: THE SYNTHESIS FOLLOWS A BIOGENIC REDUCTION METHOD, USING PLANT METABOLITES AS REDUCING AND CAPPING AGENTS.



Zero valent nanoparticles are produced through eco friendly synthesis using biological polymers or chemical reduction, maintaining minimal loading. Their precursors are generally metal salts or metal oxides. These nanoparticles display unique morphology, strong binding affinity, and excellent adsorption efficiency. They may be synthesized as single metal or bimetallic forms.Reactive surface groups—hydroxyl, amine, carboxyl, and phenolic—enhance adsorption capacity. Depending on pH, these groups exist as protonated species or coated layers, counteracting electrostatic forces between nanoparticles and pollutants.Such materials deliver exceptional benefits: rapid adsorption kinetics, easy application, and broad effectiveness against contaminants, both anionic and cationic. These materials have demonstrated remarkable effectiveness in purifying soil and water, often outperforming traditional adsorbents. Metals frequently utilized in these applications include silver, gold, zinc, copper, iron, titanium, manganese, magnesium, and cobalt. They are particularly effective in eliminating heavy metal contaminants and breaking down dyes.

TABLE 2: OVERVIEW OF DIFFERENT TYPES OF NANOPARTICLES UTILIZED FOR POLLUTANT REMOVAL FROM CONTAMINATED ENVIRONMENTS

Nanoparticles	Remediated Contaminant(s)	Operational Conditions and Removal Efficiency
Polyvinylpyrrolidone (PVP) coated iron oxide nanoparticles	Cd and Pb	The integration of bioremediation techniques utilizing Halomonas sp. has proven highly effective, achieving complete removal of lead within 24 hours and cadmium within 48 hours.
Zero-valent iron (nZVI) commercial suspension	As	pH was set at 12.2 ± 0.1. Polyacrylic acid used as a stabilizer. Maximal immobilization of As at 10% nZVI.
Graphene oxide nanoparticles (nGOx) and nZVI	Cd, Pb, Zn, Cu, and As	Immobilized Cu, Pb, and Cd; mobilized As and P.
Titanium oxide nanoparticles-bonded chitosan nanolayer (NTiO2-NCh)	Cd and Cu	pH set at 7.0. Removal assisted by heating for 60-70s. Removed 88.01% Cu and 70.67% Cd.
Palladium (Pd), Pd NPs	Cr	Pd NPs as bionanocatalyst. Completely reduced Cr6+ in 12h.
Magnetic iron oxide nanoparticles (Fe3O4 NPs) processed using Staphylococcus aureus.	Cu, Ni, Pb	Remediated 83.0–89.5% for Cu2+, 99.4–100% for Pb2+, and 92.6–97.5% for Ni2+.
ZnO NPs	Cu, Cd, Cr, and Pb	60% Cr, 70% Cu, and 85% Pb removal. pH 8.0.

EXPERIMENTAL REMEDIATION STUDY:

The potential of green nanoparticles to address soil and water pollution is evaluated through experiments conducted in controlled laboratory environments. In these tests, water samples are treated with green nanoparticles, and the reduction of heavy metals is measured using Atomic Absorption Spectroscopy (AAS). The effectiveness of green nanoparticles is subsequently compared to traditional methods, such as chemical precipitation and adsorption using activated carbon.

DATA ANALYSIS AND STATISTICAL METHODS:

Data analysis includes physicochemical assessment, statistical modeling, and geospatial analysis. The soil and water samples at affected sites (Piplantri, Morchana, and RK Marble) are analyzed for pH concentrations, heavy metal concentrations (XRD and SEM-EDS technologies, etc.).

Statistical methods such as ANOVA and regression analysis determine the effectiveness of nanoparticles in the recovery of contaminants, and analysis of major components (ACP) determines the main causes of contamination. GIS-based spatial topography visualizes the level of contamination and the effects of nanoparticles.

Multifactorial and temporary tests will monitor recovery trends over time, offering a complete assessment of green nanoparticles synthesized during the restoration of the environment.

ETHICAL CONSIDERATIONS AND ENVIRONMENTAL IMPACT ASSESSMENT:

Using green nanoparticles synthesized to relieve soil and water pollution from marble production revolves around environmental safety, community and stability wells. It is vital to ensure that nanoparticles remain non toxic, biodegradable, and free from secondary pollution. Upholding ethical standards requires transparent research practices, stakeholder engagement, and strict compliance with environmental regulations. Environmental Impact Assessment (EIA) must evaluate their efficiency in remediation while identifying possible ecological hazards during testing for environmental safety.This includes assessments of soil fertility changes, groundwater quality and biodiversity. Sustainable implementation should organize priorities in coordination with minimal environmental hazards, long-term ecosystem catering, and local conservation activities.

2. RESULTS:

The degree of soil and water contamination in marble production

1.1. CONTAMINATION OF HEAVY METALS IN SOIL

Studies have shown that marble extraction increases heavy metal concentrations such as lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni). The study documented that soil samples gathered near marblein Pakistan reached 85 mg/kg at Pb levels, exceeding the acceptable limit of 50 mg/kg of agricultural soil.

Previous studies found that marble dust deposition altered soil pH by increasing alkalinity (pH 8.5–9.5), which affected nutrient availability and microbial diversity.

1. 2 WATER QUALITY DEGRADATION

Sources of groundwater and surface water near marble prey show increased accumulation of dissolved solids (TDS), electrical conductivity (EC), and heavy metals.

The study noted a Cr concentration of 0.12 mg/L in water collected near marble processing areas.

Also, the presence of fine marble particulates in aquatic systems was found to lower dissolved oxygen (DO) levels, ultimately disrupting ecosystem balance.

2. EFFECTIVENESS OF GREEN NANOPARTICLES IN RECOVERY:

ERADICATION OF LOAD METALS FROM CONTAMINATED SOILS

Nanoparticles of iron oxide (Fe_3O_4) and zinc oxide (ZnO), derived from plant extracts, demonstrated strong adsorption and stabilization of heavy metals.

Studies reported that Fe_3O_4 nanoparticles reduced Pb and Cd levels in contaminated soil by 70–85% within 30 days of treatment.

Experimental conclution indicated that ZnO nanoparticles synthesized from Moringa oleifera extract enhanced microbial activity and accelerated the bioremediation of load metals by 60% compared to untreated soil.

Green nanoparticles exhibit higher effectiveness compared to traditional approaches, removing heavy metals faster and minimizing secondary contamination.

Unlike chemical treatments, green nanoparticles do not introduce synthetic reagents, making them a sustainable alternative for large-scale remediation.

3. CONCLUSION

Soil and water pollution from marble exploitation highlight the serious environmental impact of unregulated activities and treatment. The study systematically reports increased levels of heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni) in areas affected by mineral prey, and aims to evaluate risks to ecosystems and human poses health risks. Contamination is an insufficient result of elimination of marble suspensions and the elimination of toxin elements in groundwater leachate.

Several traditional methods for reducing contamination have been employed, such as chemical precipitation, activated carbon filtration, and soil washing adsorption. However, these methods often face limitations, including high costs, the generation of secondary pollutants, and lower effectiveness in complex environmental conditions. As a sustainable solution, green nanoparticles synthesized from plant extracts have gained significant interest Significant attention due to their eco-friendly nature, cost-effectiveness, and high remediation efficiency. Studies have shown that plant-derived (iron and zinc) oxide nanoparticles can effectively adsorb and neutralize heavy metals in contaminated soils and water bodies.

Furthermore, biogenic nanoparticles exhibit superior stability and biocompatibility, posing reduced environmental risks compared to their chemically synthesized analogues. Recent investigations revealed that remediation aided by nanoparticles not only eliminates pollutants but also enhances microbial functions and soil quality, thus supporting ecological restoration. However, challenges such as nanoparticle aggregation, potential toxicity, and scalability has to be addressed prior field-scale applications can be implemented at scale. In conclusion, although green nanoparticle remediation represents a promising solution to mitigate pollution caused by marble extraction, further investigation is needed to optimize synthesis methods, assess long-term environmental impacts, and develop cost-effective strategies for large-scale deployment. Future research should focus on integrating these novel materials into existing processing structures to improve efficiency and sustainability.

TABLE 3: EVALUATION OF GREEN NANOPARTICLES VERSUS CONVENTIONAL TECHNIQUES

Remediation Method	Heavy Metal Removal Efficiency (%)	Environmental Impact	Cost-effectiveness
Green Nanoparticles	70–90%	Eco-friendly, biodegradable	Moderate
Chemical Precipitation	60–80%	Generates sludge, secondary pollution	High
Activated Carbon Filtration	50–75%	Requires frequent regeneration	High
Phytoremediation	40–60%	Slow process, depends on plant species	low

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