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Pollution and Heavy Metal Accumulation in a Himalayan Forest Ecosystem: A Soil–Based Ecological Risk Assessment of Doodpathri, Kashmir of India

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ABSTRACT

The present study was undertaken to assess the impact of vehicular emissions on the environment of Doodpathri forest ecosystem, a pristine tourist destination in Kashmir Himalaya. Doodpathri, located approximately 45 km from Srinagar city center, is an ecologically sensitive zone dominated by fir species (Abies pindrow) and experiencing increasing tourism-related vehicular traffic. Soil samples were collected from three locations along the Doodpathri road from the entry point at Raiyar to the main tourist destination. At each location, composite samples were collected from roadside positions (within 5 meters of the road edge) and from control sites (150 meters away from the road). Heavy metal concentrations of Zinc (Zn) and Nickle (Ni) were determined using Atomic Absorption Spectrophotometry. Ecological risk indices including Geoaccumulation Index (Igeo), Contamination Factor (CF), Pollution Load Index (PLI), and Potential Ecological Risk Index (RI) were calculated to assess the degree and extent of contamination. The accumulation of heavy metals, particularly Ni and Zn, poses ecological risks to the forest vegetation and soil biota. The findings underscore the need for immediate management interventions including traffic regulation, emission control measures, and periodic monitoring of soil quality in this ecologically valuable area.

Keywords: *Vehicular emissions, roadside soil, heavy metals, ecological risk assessment, forest vegetation.*

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Introduction

The rapid expansion of road networks and increasing vehicular traffic have emerged as significant sources of environmental pollution worldwide, particularly in ecologically sensitive regions. Vehicular emissions contribute substantially to atmospheric pollution through the release of particulate matter, gaseous pollutants, and heavy metals, which subsequently deposit on adjacent soils and vegetation. This phenomenon has become a critical environmental concern, especially in pristine forest ecosystems that are experiencing growing tourism-related traffic pressure. Roadside soils act as major sinks for pollutants emitted from vehicular sources, accumulating heavy metals and other contaminants over time. The deposition of these pollutants occurs through multiple pathways, including direct emission fallout, tyre and brake wear, road surface abrasion, and atmospheric deposition. Heavy metals such as lead (Pb), zinc (Zn), copper (Cu), nickel (Ni), and cadmium (Cd) are of particular concern due to their persistence in the environment, bioaccumulative nature, and potential toxicity to soil biota and vegetation Bhat [1-2].

Forest ecosystems, particularly those in mountainous regions, are especially vulnerable to vehicular pollution due to their unique topography, meteorological conditions, and ecological characteristics.

The Kashmir Himalaya, with its rich biodiversity and fragile mountain ecosystems, faces increasing environmental pressures from tourism-related activities and associated vehicular traffic. Doodpathri, a pristine meadow and forest area in Kashmir, has witnessed a substantial increase in tourist footfall over the past decade, leading to elevated vehicular traffic along the access road from Raiyar to the main tourist destination. Heavy metals in vehicular emissions originate from multiple sources within the vehicle system. Zinc originates primarily from tyre wear, as zinc oxide is used as a vulcanizing agent in tyre manufacturing [3-4]. Nickel enters the environment through fuel combustion, particularly from diesel engines, and from the wear of engine components [2;5]. The emission rates and composition of vehicular pollutants vary depending on several factors, including vehicle type, age, maintenance status, fuel quality, driving patterns, and traffic density. Heavy-duty vehicles such as trucks and buses typically emit higher quantities of pollutants compared to passenger cars. Older vehicles with poorly maintained engines contribute disproportionately to emission loads. Stop-and-go traffic conditions, common at intersections and congested areas, result in elevated emission rates due to frequent acceleration and deceleration [6-7].

The contamination of roadside soils has implications for multiple environmental receptors. Soil microorganisms, which play crucial roles in nutrient cycling and organic matter decomposition, can be adversely affected by elevated heavy metal concentrations. Studies have documented reduced microbial biomass, altered community composition, and decreased enzyme activities in metal-contaminated roadside soils [8-9]. Soil fauna, including earthworms and arthropods, can accumulate heavy metals from contaminated soils, potentially affecting their survival, reproduction, and ecological functions.

Vegetation growing in contaminated roadside soils can take up heavy metals through root absorption, leading to accumulation in plant tissues. The extent of metal uptake varies among plant species and depends on metal bioavailability, soil properties, and plant physiological characteristics. Some plant species exhibit tolerance mechanisms that limit metal uptake or sequester metals in non-toxic forms, while others may accumulate high concentrations in edible tissues, raising food safety concerns for roadside agricultural areas [10; 4] Previous studies in the Kashmir Himalaya have documented environmental impacts of vehicular pollution in tourist destinations such as Pahalgam and Sonamarg. Research [11] the demonstrated significant accumulation of heavy metals in roadside soils, with concentrations of Pb, Zn, and Cu exceeding background levels by factors of 3-5. Alterations in soil physicochemical properties, including increased pH and reduced organic carbon, were also observed. Similarly, [5] reported substantial soil contamination in the Sonamarg forest ecosystem, with ecological risk indices indicating moderate to considerable risk levels.

Material and Methods

The research design incorporated spatial sampling along the road corridor to capture variability in traffic exposure and environmental conditions. Three sampling locations were selected along the Doodpathri road from the entry point at Raiyar to the main tourist destination, representing different traffic intensities and environmental settings. At each location, samples were collected from both roadside positions (within 5 meters of the road edge) and control positions (150 meters away from the road).

Soil samples were collected from the surface layer (0-10 cm depth) using a stainless-steel soil auger. This depth was selected because traffic-derived heavy metals accumulate primarily in surface soils, and this layer is most relevant for assessing recent contamination. Samples were stored in a cool, dark place during transport to minimize any changes in soil properties. were immediately processed for analysis. A portion of each sample was air-dried for heavy metal determination.

Heavy metal concentrations (Zn and Ni) were determined using Atomic Absorption Spectrophotometry (AAS) following acid digestion of soil samples. This method involves complete digestion of soil samples using strong acids, followed by measurement of metal concentrations in the digest using AAS. On the basis of the heavy metal concentrations, Ecological risk indices including Geoaccumulation Index (Igeo), Contamination Factor (CF), Pollution Load Index (PLI), and Potential Ecological Risk Index (RI) were calculated to assess the degree and extent of contamination.

Geoaccumulation Index (Igeo)

The Geoaccumulation Index (Igeo) was calculated to assess the degree of heavy metal contamination in roadside soils. The index compares measured metal concentrations with geochemical background values, accounting for natural variability. The Igeo was calculated using the formula:

$$Igeo = \log_2[Cn / (1.5 \times Bn)]$$

where:
- Cn = measured concentration of metal n in the sample (mg/kg)
- Bn = geochemical background value for metal n (mg/kg)
- 1.5 = correction factor to account for natural variability

Background values for Kashmir soils were obtained from published literature.

Contamination Factor (CF)

The Contamination Factor (CF) was calculated as a simple ratio of measured metal concentration to background concentration:

$$CF = Cn / Bn$$

where:
- Cn = measured concentration of metal n in sample (mg/kg)
- Bn = background concentration of metal n (mg/kg)

Pollution Load Index (PLI)

The Pollution Load Index (PLI) was calculated to provide an integrated assessment of contamination by multiple metals. The PLI is the nth root of the product of n Contamination Factors:

$$PLI = (CF_1 \times CF_2)^{(1/2)}$$

where CF_1 and CF_2 are the Contamination Factors for Zn and Ni and respectively.

Potential Ecological Risk Index (RI)

The Potential Ecological Risk Index (RI) was calculated to assess the potential ecological risk of heavy metal contamination, considering both contamination levels and the toxicity of individual metals. The index was calculated as:

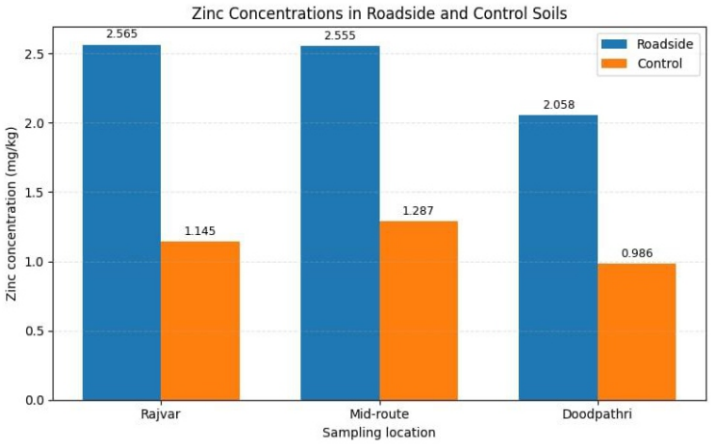
$$RI = \Sigma E_i = \Sigma (T_i \times Cf_i)$$

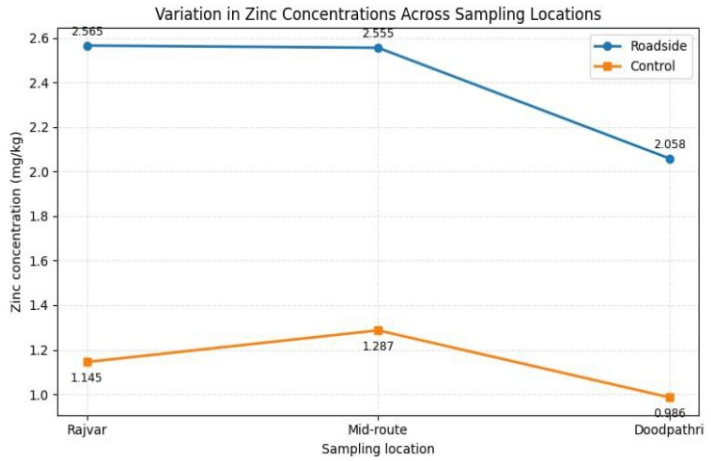
where:
- E_i = potential ecological risk factor for metal i
- T_i = toxic response factor for metal i
- CF_i = Contamination Factor for metal i

Results and Discussion

Zinc (Zn)

Zinc concentrations in roadside soils were substantially elevated compared to control sites, with zinc showing the highest absolute concentrations among all metals studied. The results of zinc analysis are presented in graphs below

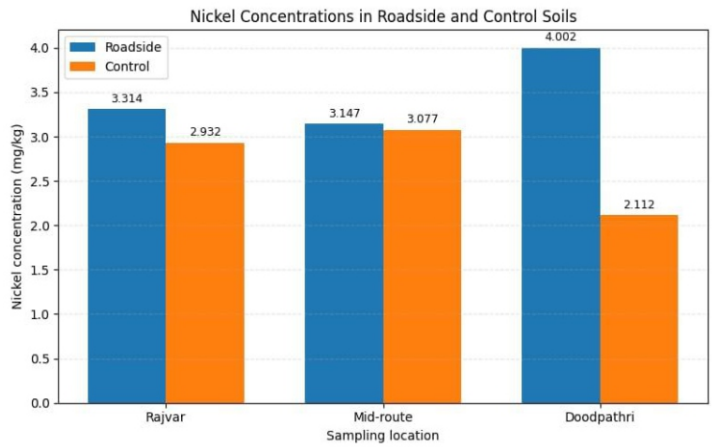


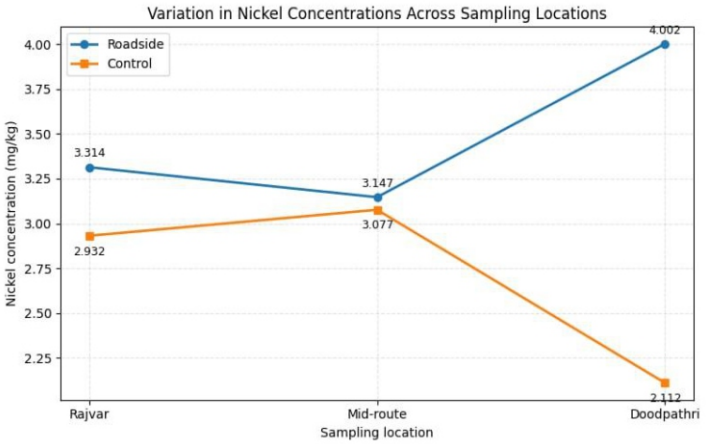


The results demonstrate that zinc concentrations were significantly higher at roadside locations compared to control sites across all three sampling locations. The overall mean Zn concentration at roadside sites was 2.392 mg/kg, compared to 1.136 mg/kg at control sites. This difference is highly significant ($p < 0.001$).

Nickel (Ni)

Nickel concentrations in roadside soils were moderately elevated compared to control sites across all sampling locations. The results of nickel analysis are presented in graphs below





The results demonstrate that nickel concentrations were significantly higher at roadside locations compared to control sites at two sampling locations and non-significant higher at roadside of location 2. The overall mean Ni concentration at roadside sites was 3.487 mg/kg, compared to 2.707 mg/kg at control sites. This difference is significant ($p < 0.05$).

Geo-accumulation Index (Igeo)

The Geo-accumulation Index was calculated for both the heavy metals at roadside and control sites to assess the degree of contamination.

Zinc (Zn): Igeo values at roadside locations range from 0.89 to 1.56, indicating uncontaminated to moderately contaminated at Location 1, and moderately contaminated at Locations 2 and 3. The progressive increase in Igeo values from Location 1 to Location 3 reflects increasing traffic intensity.

Nickel (Ni): Igeo values at roadside locations range from 0.30 to 1.12, indicating uncontaminated to moderately contaminated at Locations 1 and 2, and moderately contaminated at Location 3.

Contamination Factor (CF)

The Contamination Factor was calculated for both the heavy metals at roadside sites to assess contamination levels. The Contamination Factor results indicate moderate to considerable contamination for all heavy metals at roadside locations:

Zinc (Zn): CF values range from 2.79 to 4.41, indicating moderate contamination at Location 1 and considerable contamination at Locations 2 and 3. The mean CF of 3.65 indicates substantial contamination. The progressive increase in CF values reflects increasing traffic intensity.

Nickel (Ni): CF values range from 1.85 to 3.27, indicating moderate contamination at Locations 1 and 2, and considerable contamination at Location 3. The mean CF of 2.57 is the lowest among all metals, consistent with nickel's lower enrichment. Nevertheless, the CF values confirm moderate to considerable contamination.

Pollution Load Index (PLI)

The Pollution Load Index was calculated for roadside sites to provide an integrated assessment of contamination by multiple metals.

Pollution Load Index at Different Sampling Locations

Location	PLI	Classification
Location 1 (Raiyar)	1.82	Progressive deterioration
Location 2 (Mid-route)	2.45	Progressive deterioration
Location 3 (Doodpathri)	2.94	Progressive deterioration
Mean	2.40	Progressive deterioration

The Pollution Load Index results indicate progressive deterioration of soil quality at all roadside locations. PLI values range from 1.82 at Location 1 to 2.94 at Location 3, with a mean value of 2.40. All PLI values exceed 1, confirming that roadside soils are experiencing progressive deterioration due to heavy metal accumulation.

Potential Ecological Risk Index (RI)

The Potential Ecological Risk Index was calculated for roadside sites to assess the potential ecological risk of heavy metal contamination, considering both contamination levels and metal toxicity.

Zinc (Zn): E(Zn) values range from 2.8 to 4.4, indicating low risk at all locations. Despite high absolute concentrations, the very low toxic response factor for zinc (T = 1) results in minimal contribution to overall risk.

Nickel (Ni): E(Ni) values range from 9.3 to 16.4, indicating low risk at all locations. The moderate toxic response factor for nickel (T = 5) combined with moderate contamination results in low individual risk.

The Potential Ecological Risk Index results indicate moderate ecological risk at all roadside locations. All RI values fall within the moderate risk category (150-300), indicating that current heavy metal contamination poses moderate potential ecological risk to the forest ecosystem. The progressive increase in RI values from Location 1 to Location 3 reflects increasing traffic intensity and metal accumulation. Location 3, with the highest traffic volume, shows the highest RI value, approaching the threshold for considerable risk (RI = 300). Continued traffic growth could push RI values into the considerable risk category.

Comparison with previous studies shows similar patterns, [4] reported RI values indicating moderate to considerable risk in roadside agricultural soils in India, with cadmium and lead contributing most significantly, Xu et.al., (2021) documented RI values of 150-250 in agricultural soils alongside highways in China, indicating moderate risk. [1] reported RI values of 120-280 in roadside soils in Iraq, indicating low to moderate risk. The RI values in Doodpathri are within the range reported for moderate-traffic roads.

Conclusion

Current heavy metal contamination poses moderate potential ecological risk to the Doodpathri forest ecosystem. The Potential Ecological Risk Index indicates moderate risk.While moderate risk does not indicate immediate severe impacts, it suggests that current contamination levels could affect sensitive species or ecological processes. The degree of soil contamination and ecological risk increases with traffic intensity. The progressive increase in metal concentrations, contamination indices, and risk values from Location 1 to Location 3 demonstrates a clear dose-response relationship between traffic exposure and environmental impacts. The pristine Doodpathri forest ecosystem is vulnerable to vehicular pollution impacts.

Despite its designation as an ecologically sensitive area and its relatively remote location, the ecosystem is experiencing measurable environmental degradation due to tourism-related traffic. The forest soils, characterized by high organic matter and acidic pH, are particularly vulnerable to contamination. Continued traffic growth without management interventions will lead to further environmental degradation. The progressive increase in contamination with traffic intensity suggests that the ongoing growth in tourism and associated vehicular traffic will result in higher contamination levels and greater ecological risks in the future. The study provides a critical baseline for future monitoring and management. The comprehensive data on soil properties, heavy metal concentrations, and ecological risks establish a baseline against which future changes can be measured. This baseline is essential for tracking temporal trends and evaluating the effectiveness of management interventions.

Conflict of Interest: No potential competing interest was reported by the authors.

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