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A Synoptic Review Of Heavy Metal Accumulation In Soils Along Urban Roadsides

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Abstract:
Heavy metal poisoning in roadside soils is a worldwide environmental issue with serious consequences for both ecological health and human well-being. This study provides a detailed summary of the state of heavy metal pollution along roads, spanning multiple locations and centuries. The research found a pattern of contamination in major and medium-sized cities around the world, with cadmium (Cd), chromium (Cr), zinc (Zn), nickel (Ni), copper (Cu), and lead (Pb) appearing as common pollutants. Temporal dynamics, specifically the impact of road age on heavy metal dosages, are investigated, offering light on the long-term consequences of vehicular traffic on soil pollution.

The investigation delves into specific case studies, including the historic levels of lead in Kuala Lumpur and the shift from leaded to unleaded gasoline. Regional disparities in zinc and cadmium concentrations underscore the complex nature of heavy metal contamination, necessitating nuanced, area-specific mitigation strategies. Elevated copper levels in England, Korea, and Greece highlight the triad of concern in various geographical settings. Furthermore, the research compares heavy metal concentrations in Indian cities, emphasizing the influence of regulatory measures on contamination levels. The drastic reduction in lead levels in Kolkata post the discontinuation of leaded petrol signifies the effectiveness of environmental interventions. Conversely, the complex heavy metal predicament in Delhi underscores the intricate relationship between vehicular emissions, traffic congestion, and contamination.

The study concludes with a global perspective on heavy metal contamination, emphasizing its meaningful ecological and anthropological health hazards. The regional and temporal variations discovered in this study give essential insights for informed decision-making, regulatory actions, and long-term urban planning to limit the negative consequences of heavy metal pollution in roadside soil.

Keywords: Heavy metal contamination, Roadside soil, Cadmium, Chromium, Zinc, Nickel, Copper, Lead, Urban pollution, Environmental health.

1. Introduction:

Environmental pollution, a serious global concern, manifests in a variety of ways, with soil contamination being a major issue. Heavy metals are a particularly harmful aspect of soil contamination. Heavy metals are differentiated by their high densities, atomic weights, and atomic numbers, which render them toxic even at low concentrations. This category contains common substances like mercury (Hg), cadmium (Cd), lead (Pb), chromium (Cr), arsenic (As), zinc (Zn), copper (Cu), and nickel (Ni)[1]. Because of their persistence and possible biological toxicity, these heavy metals constitute a significant hazard to both the environment and public health. Their entry into soil ecosystems is facilitated by diverse anthropogenic activities, encompassing industrial emissions, mine tailings, waste disposal, fertilizer and pesticide applications, and atmospheric deposition[2]. Despite being colorless and odorless, heavy metal contamination in soil operates as a latent hazard. Its effects may not be immediately apparent, but when environmental conditions change or tolerance thresholds are exceeded, the activation of heavy metals can unleash severe ecological damage, akin to a chemical time bomb[3].

Roadside soils emerge as crucial reservoirs for pollutants originating from vehicular traffic, exposing nearby populations to biologically toxic trace metals through inhalation, ingestion, and dermal contact. Sanitation workers, residents in proximity to roads, and pedestrians are particularly vulnerable[4]. Furthermore, these metal-contaminated soils can have far-reaching effects on the urban ecosystem, influencing the ecological environment through the uptake of metals by plants and animals and transport via rainwater into permanent water bodies[5].The escalation of vehicular traffic over the past two decades has led to accelerated deposition rates of heavy metals, contributing to the degradation of roadside soils[6]. The dominant sources of air pollutants have shifted towards vehicular emissions, a trend exacerbated by the substantial increase in traffic on roads[7].

The deposition of heavy metals in roadside soils is a multifaceted process influenced by factors such as traffic volume, highway operation time, tire-road friction, altitude, wind patterns, vegetation coverage, and terrain. Dust deposition, precipitation, and runoff are the primary mechanisms through which heavy metals are introduced to roadside soils[8]. Notably, the relative amounts and distribution of heavy metals are intricately linked to these dynamic variables.

While pollutants like zinc and lead show high bioavailability and swift dispersion, concentrations reducequickly with distance from the roadway. However, concentrations between 0.5 and 5.0 meters from the pavement remain significant, with negligible concentrations beyond 10 meters[9]. The deposit and intensity of heavy metals in roadside soil exhibit spatial variability, emphasizing the localized nature of the pollution[10].

Beyond direct emissions into the atmosphere, vehicular pollutants accumulate on urban road surfaces throughout dry periods, forming road-deposited sediments that preserve toxic pollutants[11]. Given the serious environmental, ecological, and health consequences of heavy metal contamination, various studies have been conducted to quantify the level of contamination in soils near major roads[12].

Heavy metal accumulation in the environment is mostly induced by vehicle operations such as combustion, automotive wear (tires, brakes, and engines), oil leaks, and corrosion. Tyre wear, in particular, has been identified as a source of manganese in traffic [13]. Several metals, including Mg, Cu, Cr, and Ni, are essential components of vehicle engines, chassis, and pipework. Zinc, from tire dust and galvanized vehicle parts, and copper, from brake abrasion and radiator corrosion, both contribute to the heavy metal load[14]. Furthermore, metals such as Fe, Cu, and Zn, which are important components of automobile alloys, pipes, cables, and tires, are released into the surrounding atmosphere through mechanical abrasion and wear and tear[12].

2. Sources of Heavy Metal Contamination in Soils

Heavy metals are found naturally in soil as a result of pedogenetic mechanisms and parent material degradation. They are often present at low levels (<1000 mg kg−1) and rarely cause toxicity [15, 16]. The actions of humans, on the contrary , disrupts and increases the organic geochemical cycle of metals, which leads to the formation of one or more heavy metals in rural and urban soils that go over the established baseline values, endangering human health, plants, animals, ecosystems, and various environmental media[16].

A variety of mechanisms contribute to the transition of these heavy metals into pollutants in soil. To begin, the man-made cycles that produce these metals work at a faster rate than their natural counterparts. Second, these metals are transmitted from mining activities to a variety of environmental sites, increasing the risk of direct exposure. Third, the amounts of metals in rejection materials are significantly higher than those that normally occur in the receiving environment. Finally, the chemical forms (species) of these metals in the receiving environment can enhance bioavailability [16][17].

Anthropogenic sources improve heavy metal transport and bioavailability in soil compared to pedogenic or lithogenic sources [18][19]. Solids containing these metals in contaminated regions come from a variety of human-caused sources, including metal mining tailings, inadequately secured landfills for high metal waste, leaded gasoline and lead-based paints, fertilizer use, livestock manure, sewage sludge (biosolids), composting, pesticides, coal combustion residues, petrochemicals, and being subjected to the atmosphere[20].[21][22]

3. Pathways of Heavy Metal Entry into the Human Body:

The discharge of hazardous pollutants into the environment has been intricately associated with an extensive array of health risks for humans. Heavy metals, among these contaminants, are key contributors to chronic diseases, causing harm by interfering with the normal functioning of biological cells and organs. These heavy metals enter the body through three main routes: ingestion, inhalation, and interaction with the skin.[20]

3.1. Ingestion:

One of the principal avenues through which individuals are exposed to heavy metals is through the ingestion of corrupted substances. This can include the intake of food and water that has absorbed heavy metals from polluted soils. The ingestion route underscores the systemic nature of heavy metal contamination, as these toxic elements become assimilated into the human body, potentially leading to long-term health implications[23].

3.2. Inhalation:

Inhalation serves as another critical pathway for the entry of heavy metals into the human system. Airborne particles carrying heavy metal contaminants can be inhaled, introducing these toxic elements directly into the respiratory system. Once inhaled, these particles can navigate into the bloodstream, spreading throughout the body and posing risks to various organs and tissues.[23]

3.3. Dermal Contact:

The third major pathway for the introduction of heavy metals into the human body is through dermal contact. Skin, being the largest organ, can absorb these contaminants upon direct contact with polluted materials. This pathway is particularly relevant in scenarios where people come into physical contact with polluted soil, water, or other environmental matrices. The absorption of heavy metals through the skin emphasizes the pervasive nature of environmental contamination and its potential impact on human health[20][23].

Heavy metals enter the human body through three fundamental pathways: ingestion, inhalation, and skin contact, all of which pose long-term health risks[24]. These channels connect heavy metals in roadside soils to the rest of the environment, possibly into the food chain.

4. Major impact of heavy metal in the environment

Lead (Pb): Recognized for its extreme toxicity, Pb has been extensively studied for its detrimental effects on the brain, nervous system, red blood cells, and kidneys[25]. Both inhalation and ingestion pose significant health risks, with studies revealing elevated Pb levels in the blood of approximately 30% of Chinese children, exceeding established safety standards[26].

Chromium (Cr): Cr mobility in soils is determined by absorption features such as clay concentration, iron oxide content, and the presence of organic matter, which has been linked to allergic dermatitis in humans. Surface runoff delivers soluble chromium complexes to surface waters, potentially contaminating groundwater [27].

Cadmium (Cd): Cd, which has a high bio-persistence, disrupts calcium metabolism, potentially causing calcium insufficiency and leading in cartilage disorders and bone fractures. Cd, classified as the sixth most hazardous chemical affecting human health, calls for more attention and regulatory actions.[28].

Nickel (Ni): Despite its important role in modest doses, Ni becomes dangerous when the maximum tolerated quantity is surpassed, contributing to many types of cancer in animals. While microorganisms may initially experience growth inhibition due to Ni presence, they frequently develop resistance throughout time, minimizing possible ecological effects [29].

Copper (Cu): Copper is the third most commonly used metal globally, crucial for the growth of plants and animals, and plays a role in producing blood hemoglobin in humans. Nevertheless, high amounts could lead to anemia, liver and kidney issues, along with stomach and intestinal issues [30].

Zinc (Zn): Zn deficiency is critical for human health and can result in birth abnormalities. In contrast, elevated Zn levels can disrupt soil activity by suppressing microorganisms and earthworms, preventing organic matter breakdown[31].

The harmful effects of Pb are well-documented, with more extensive research than other trace metals, due to its damaging impact on the brain, neurological system, red blood cells, and kidneys. Exposure to lead can happen through breathing or ingestion, with consistent effects. Studies have shown that heavy metals in soil can penetrate the human body through skin contact and breathing in dust, leading to negative impacts on children's health in particular. Around 30% of Chinese children have blood Pb levels exceeding the residential standard of 100 g/L [26]. Cr is linked to human allergic dermatitis. The majority of Cr dumped into natural streams settles as sediments[33]. Cd is exceedingly bio-persistent but has low danger potential; once ingested by an organism, it remains there for many years[34]. It can affect calcium metabolism, causing calcium deficiency, cartilage deterioration, and bone fractures. The Agency for Toxic Substances and Disease Registry has ranked Cd as the sixth most toxic substance to human health. Ni is a trace element found in small concentrations in nature and is essential in minimal quantities. However, exceeding the maximum tolerated level can be harmful. This can lead to numerous types of cancer in animals' bodies[29]. The greater the proportion of Ni compounds discharged into the environment and absorbed by sediment or soil particles, the more often they leach down to nearby groundwater. Microorganisms may encounter growth inhibition when exposed to ni, but they tend to build up resistance to it over time. Ni does not build up in plants or animals, thus it does not increase inconcentration along the food chain[34]. Copper is the third most commonly used metal worldwide and a crucial micronutrient for the growth of plants and animals. In humans, it plays a role in hemoglobin production. Despite being essential, excessive copper intake can lead to anemia, liver and kidney harm, as well as stomach and intestinal discomfort[30].Zn is vital for human health since a lack of it can cause birth deformities, but an excess of it can cause health problems that disrupt soil activity by killing microbes and earthworms, slowing the breakdown of organic matter[31].

5. Global Overview of Heavy Metal Contamination in Roadside Soil:

Contamination of roadside soils by heavy metals is a pervasive issue in large- and medium-sized cities worldwide, transcending continents and presenting a significant environmental concern[35]. The array of heavy metals encountered in these soils varies across different regions, with Cd, Cr, Zn, Ni, Cu, and Pb emerging as the most prevalent, while Hg, As, Fe, and Mn exhibit comparatively lower concentrations. This comprehensive overview encapsulates studies conducted in diverse locations, spanning Asia, North America, Europe, and Africa, revealing a global pattern of heavy metal presence along roadways.

5.1. Temporal Impact on Heavy Metal Concentrations: The Role of Road Age

Researchers shed light on the temporal dynamics of heavy metal concentrations, underscoring the influence of road age on soil contamination. Older road segments, having weathered more years of vehicular traffic, tend to exhibit heightened concentrations of heavy metals. Particularly, the concentration of lead (Pb), primarily emitted by gasoline vehicles, persists in roadside soils despite years of leaching by rainfall. Intriguingly, the study posits that the age of the road segment directly correlates with the extent of heavy metal accumulation[36]

5.2. Lead Contamination Trends: A Shift from Leaded to Unleaded Gasoline

Examining the specific case of lead contamination, historical data from Kuala Lumpur [37]indicates a staggering Pb content of 2466 ppm in roadside soil, surpassing thresholds set by CCME[38] and[39] from Spain, who reported 1505.4 ppm. The Kuala Lumpur data, dating back to 1989, coincides with an era when leaded gasoline usage was prevalent. Conversely, the alarming Pb levels in Spain, even after the cessation of leaded gasoline usage, underscore the lasting impact of historical pollution[37].

5.3. Zinc and Cadmium Challenges: Regional Disparities

Zinc (Zn) levels in roadside soils have been consistently reported above threshold values in various regions, including England, Korea, Turkey, Spain, and Bangkok [40][41][42][39][43]. Conversely, cadmium (Cd) concentrations, while below the threshold of CCME (2007)[44], surpass limits established by NEPA,1995[33] in multiple global locations. These regional disparities underscore the complex nature of heavy metal contamination and the need for nuanced, area-specific mitigation strategies.

5.4. High Copper Levels: A Triad of Concern in England, Korea, and Greece

Many researchers report that the elevated copper (Cu) levels in roadside soils in England, Korea, and Greece, respectively. These findings highlight the widespread nature of Cu contamination along roadways, indicating a triad of concern in various geographical settings[40][45][41]

5.5. Exemplary Case: Beijing's Prowess in Mitigating Heavy Metal Pollution

In the realm of heavy metal research, study in Beijing stands out as exemplary[46]. This area uniquely showcases levels of heavy metals consistently below established thresholds, suggesting successful mitigation efforts or distinctive local factors contributing to a more favorable soil environment.

Table 1. Heavy Metal Concentration in PPM across different parts of the world.

Cities/Countries	Cd	Cr	Cu	Pb	Zn	Ni	Reference
Kuala Lumpur	2.9**	-	35.5	2466*	467	-	[37]
Ottawa	0.37**	43.3	65.84	39.05	112.5	15.2	[47]
France	0.53**	47	20	43.1	43.1	14.7	[48]
England	1.62**	-	466.9*	48	532*	41.1	[40]
Korea	4.3**	182.1*	445.6*	214.3	2665	89.6*	[41]
Syria	-	57	34	17	103	39	[49]
Turkey	0.1-14.6**	17-81	12-144	28-312	33-733*	16-217	[50]
Jordan	1.7**	-	177*	236	358	88*	[51]
Guangzhou	0.5**	-	62.5	108.5	169.2	25.6	[52]
Beijing	0.15	35.6	23.7	28.6	65.6	27.8	[46]
Shanghai	0.52**	107.9*	59.2	70.6	301.4	31.4	[53]
Spain	3.76**	-	57	1505.4	596*	-	[39]
Egypt	0.82**	36.9	-	25.38	234.6	634.4[1]*	[54]
Bangkok	1.09**	152	14.7	53.4	660.0*	-	[43]
Canada	0.51**	197.7*	162*	182.8	200.3	58.8*	[55]
Iran	1.53**	63.7*	60.1	46.5	94	37.5	[56]
Nigeria	1.5**	2.0	56.5	61	72	1.2	[57]
Greece	1.33**	-	247*	44.8	44.8	58*	[45]
Saudi Arabia	7.46**	65.43**	550.61**	140.7**	487.52**	51.29*	[58]
China	8.6**	54.8	44.1	57.4	24.2	1.53	[5]

UAE	0.48	306.33**	–	50.05	173.01	O.3	[59]

*Indicates higher than the threshold level of CCME (2007), Industrial area
**Indicates higher than the threshold level of NEPA (1995).

Table 2. The threshold value of heavy metals(PPM)

Countries	Cd	Cr	Cu	Pb	Zn	Ni	Reference
China soil guidelines[a]	0.3	200	100	300	250	50	[60]
Canada soil guidelines[b]	10	64	63	140	200	50	[44]
Canada soil guidelines[c]	22	87	91	600	360	50	[44]

[a] Class 11. Metal levels in class 11 are threshold values established to protect agricultural production and maintain human health.
[b] Residential/parkland use.
[c] Industrial land usedStatus in India

Table3. Heavy metal content in roadside soils (ppm) in India.

Cities	Cd	Cr	Cu	Pb	Zn	Ni	Reference
Calcutta	3.12*	54	44	536	159	42	[61]
Delhi	2.65*	148.8**	191.7*	36.4	120.7	284.5*	[62]
Kolkata	–	1.31	1.97	2.47	–	1.96	[63]

*Indicates higher than the threshold level of CCME (2007), Industrial area
**Indicates higher than the threshold level of NEPA (1995).

Through a comparative examination spanning two decades, an in-depth investigation into heavy metal concentrations in the Indian cities of Calcutta, Kolkata, and Delhi unveils intricate dynamics associated with roadside soil contamination. The historical dataset from 1999 paints a concerning picture of Calcutta, showcasing exceptionally high lead (Pb) levels at 159 ppm, surpassing established environmental thresholds[61]. However, a subsequent study conducted in 2020 within Kolkata reveals a remarkable and drastic reduction in Pb levels to 2.47 ppm. This significant decline is attributed to the discontinuation of leaded petrol usage, marking a pivotal shift in environmental practices[64].

On the other hand, the metropolis of Delhi confronts a complex heavy metal predicament. Historical data from a study in 1999 reveals elevated Cd levels in both Calcutta and Delhi, exceeding the threshold set by the National Environmental Protection Agency (NEPA) in 1995. The subsequent investigation in Delhi, undertaken in 2016, reveals continually high levels of cadmium, as well as worrying quantities of chromium (Cr), copper (Cu), and zinc (Zn)[62]. These findings highlight the significant influence of vehicle emissions and traffic-related activities on heavy metal pollution in Delhi's roadside soil. This temporal and spatial study provides unique insights into the intricate interplay of regulatory measures, urban characteristics, and heavy metal profiles, adding to a comprehensive knowledge of environmental dynamics in these different Indian cities [62, 65].

Conclusion:

In conclusion, this comprehensive exploration into the global status of heavy metal contamination along roadside soils underscores the pervasive environmental threat posed by these toxic elements. The intricate dynamics of heavy metal concentrations in various cities, spanning continents and decades, reveal a complex interplay of factors influencing soil contamination. From the historical levels of lead (Pb) in Kuala Lumpur, reflective of leaded gasoline usage, to the drastic reduction in Pb concentrations in Kolkata following the ban on leaded petrol, the impact of regulatory measures on heavy metal levels is evident. The case of Morena highlights the influence of urban characteristics, such as low traffic congestion and widespread bicycle use, in mitigating heavy metal accumulation.

The contrasting heavy metal profiles of Calcutta, Kolkata, and Delhi emphasize the need for region-specific mitigation strategies. Delhi, characterized by persistent elevated levels of cadmium, chromium, copper, and zinc, reflects the intricate relationship between vehicular emissions, traffic congestion, and heavy metal contamination. This study provides critical insights into the spatial and temporal variations of heavy metal concentrations, shedding light on the global pattern of contamination along roadways.

Furthermore, the global overview presented in this research paper encompasses diverse cities and countries, highlighting the prevalence of Cd, Cr, Zn, Ni, Cu, and Pb as common contaminants. The temporal influence on heavy metal concentrations, particularly the role of road age, elucidates the lasting impact of vehicular traffic on soil contamination. The exemplary case of Beijing, showcasing consistently low levels of heavy metals, serves as a benchmark for successful mitigation efforts.

Ultimately, heavy metal contamination in roadside soils poses not only environmental but also significant human health risks through multiple exposure pathways, including ingestion, inhalation, and dermal contact. The identified sources of contamination, from vehicular activities to anthropogenic interventions, underscore the urgent need for comprehensive regulatory measures and sustainable urban planning. As we grapple with the global challenge of heavy metal contamination, this research contributes valuable insights to the scientific discourse, paving the way for informed decision-making and targeted interventions to safeguard both the environment and public health.

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