ACADEMIA ROMÂNĂ

Revue Roumaine de Chimie

https://www.icf.ro/rrch/

Rev. Roum. Chim.,
2024, *69*(9), 483–490
DOI: 10.33224/rrch.2024.69.9.04

Dedicated to the memory of
Academician Dr. Eng. Emilian BRATU (1904–1991)

THE CRITICAL ANALYSIS OF AIR POLLUTION AND SOIL POLLUTION WITH MICROPLASTICS AND HEAVY METAL IN RWANDA, ROUMANIA AND CHINA

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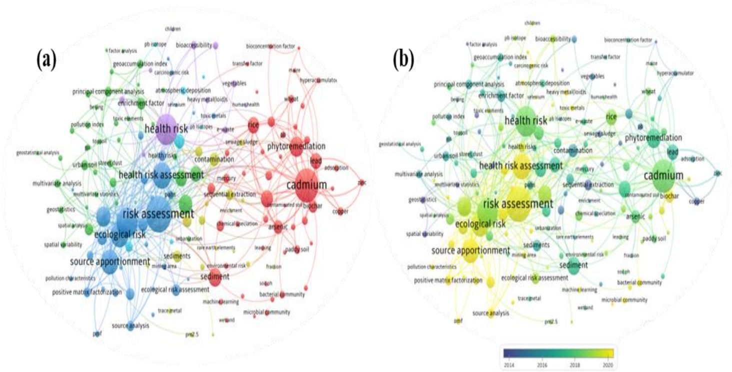
Received July 2, 2024

Air and soil pollution is a global concern due to the substantial environmental and health hazards they bring. This critical analysis conducted a comparative analysis of the main pollution sources, pollution levels, and pollution impacts in Rwanda, Roumania, and China through an extensive review of existing literature. The results indicate that the presence of particulate and gaseous pollutants, microplastic particles (Mps), and heavy metals in the air and soil poses significant global health and environmental risks. Despite various governmental efforts, managing these pollutants remains challenging. Rwanda struggles with biomass-related air pollution, Roumania with heavy metal contamination from past industries, and China with severe soil pollution exacerbated by population growth. The study emphasizes the need for stronger regulations, public awareness, research investment, and international collaboration to address these challenges effectively.



INTRODUCTION

Air pollution, water pollution, soil pollution, waste disposal, and other issues need to be solved urgently. It is reported that there are 340,000 contaminated soils in Europe, 85% of which have not been repaired. More than 1.2 billion people in 50 countries/regions worldwide lack access to clean drinking water (Paya & Rodriguez, 2018). With the advancement of technology, many plastic products are used in daily life. According to statistics, Mps have invaded the human placenta, with each gram

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of placental tissue containing 6.5–685 micrograms of Mps[1–3], and immune systems [4]. The presence of these pollutants not only has a direct impact on environmental quality but also poses a potential hazard to human health through the food chain and respiratory pathways. Therefore, it is of great significance to systematically study the sources, distribution, and impacts of these pollutants on ecosystems and human health on a global scale.[5]

The objective of this study is to conduct a critical analysis of pollution factors in Rwanda, Roumania, and China, representing Africa, Europe, and Asia, respectively. By examining these countries, the study aims to understand how varying economic development levels, geographical locations, and industrial practices influence environmental pollution. The analysis will focus on identifying differences in pollution standards and measures employed by each country, providing insights into how these factors impact environmental management across diverse contexts.

EXPERIMENTAL

This study employs a qualitative research design, focusing on a comprehensive literature review and comparative critical analysis. The critical analysis approach is used to examine and compare the pollution levels and mitigation strategies related to particle and gaseous pollutants, Mps, and heavy metal pollution in Rwanda, Roumania, and China.

Data for this analysis is gathered from peer-reviewed journal articles, government reports, international environmental organization publications, and other credible sources of secondary data. Studies and reports published within the last 10 years are prioritized to ensure relevance. Additionally, sources that provide specific data or insights in Rwanda, Roumania, and China are included. Studies lacking empirical data or not directly related to the pollutants of interest in the specified countries are excluded.

A systematic review of the literature is conducted to identify and synthesize information on particle and gaseous pollutants, Mps, and heavy metal pollution in soil and air in the three countries. Key themes such as sources of pollution, levels of contamination, environmental and health impacts, and regulatory responses are identified. A comparative framework is developed to systematically compare the findings across the three countries. For particle and gaseous pollutants, the comparison includes types, sources, levels, and mitigation strategies. For Mps, the analysis focuses on sources, types, environmental and health impacts, and regulatory measures. For heavy metal pollution, the examination covers sources, contamination levels, health impacts, and mitigation efforts.

To ensure reliability, the review process adheres to predefined inclusion and exclusion criteria, maintaining consistency throughout. Validity is ensured by using multiple sources and cross-referencing data to confirm the accuracy and credibility of the findings. Ethical considerations include maintaining transparency in the selection and analysis of literature and proper attribution of all sources to avoid plagiarism.

RESULTS AND DISCUSSION

Research hotspots and evolution of soil heavy metal pollution in China

Significant volumes of wastewater, solid waste, and waste gases containing heavy metals are being added to the soil because of the fast-moving urbanization and industrialization processes. According to statistics, heavy metal contamination affects 20% of agricultural land worldwide, but to different degrees. In China alone, N1.0 million km2 (100 million ha) of land are heavy metal-polluted[6]. The vast majority of pollutants in China are inorganic, with an exceedance rate of 82.8%. The exceedance rates for heavy metals in soil are as follows: cadmium at 7.0%, mercury at 1.6%, arsenic at 2.7%, copper at 2.1%, lead at 1.5%, and zinc at 0.9% [7].

Heavy metal contamination of soil is widespread in some parts of China; in some agricultural soils, concentrations of heavy metals reach more than multiple times the national guidelines, and in severe situations, even more than hundreds of times. Conversely, heavy metal concentrations in soil, groundwater, and various water bodies in many countries exceed acceptable limits due to industrialization, population growth, and inadequate management policies. These heavy metals may originate from human activities such as industrial, mining, and agricultural emissions. This has a significant impact on the survival and health of microorganisms, animals and plants. Due to their persistence, rapid accumulation and non-biodegradability, heavy metals cause environmental pollution in the natural environment. Therefore, in recent decades, this problem has developed into one of the most influential problems worldwide.[8]

Based on web of science statistics, Chinese research papers on soil heavy metals constitute 12.66% of the total number of publications on this topic. This shows the severity of soil heavy metal pollution in China. Using VOSViewer 1.6.20, 7514 papers were analyzed and keyword cluster analysis was used to interpret the current research hotspots in the field of heavy metal pollution assessment in China. This network visualizes the relationships between keywords, highlighting their interconnections. The co-occurrence network can be divided into three clusters (Fig. 1a).

Cluster 1 primarily encompasses studies on types of heavy metals. The primary heavy metal elements of concern within this cluster include cadmium (362 mentions), lead (132 mentions), arsenic (107 mentions), and zinc (44 mentions). It can be seen that cadmium is a heavy metal element that is the focus of research in the field of soil heavy metal pollution remediation outside China. A significant focus is placed on the migration of heavy metals in plants, particularly in relation to China's main food crops, rice (136 mentions) and wheat (58 mentions). These crops are central to research efforts due to their importance in the region's agriculture and food safety.

Cluster 2 primarily encompasses studies on various soil heavy metal remediation techniques. The high frequency of keywords such as "phytoremediation (178 mentions)", "accumulation (73 mentions)", and "biochar(97 mentions)" indicates that phytoremediation methods and chemical remediation are research focuses in this field, also shows that exploring hyperaccumulator plants and passivation materials are a hot topic for Chinese scholars[9].

Cluster 3 primarily includes various factors and methods related to soil heavy metal pollution assessment. The most extensively studied assessment factor is risk assessment (538 mentions), which health risk assessment (324 mentions) and ecological risk (245 mentions). This is followed by studies on the spatial distribution of pollutants (308 mentions) and source analysis (238 mentions). This indicates that risk assessment of soil heavy metal pollution to ensure human health and ecological environment friendliness has also received attention in China.

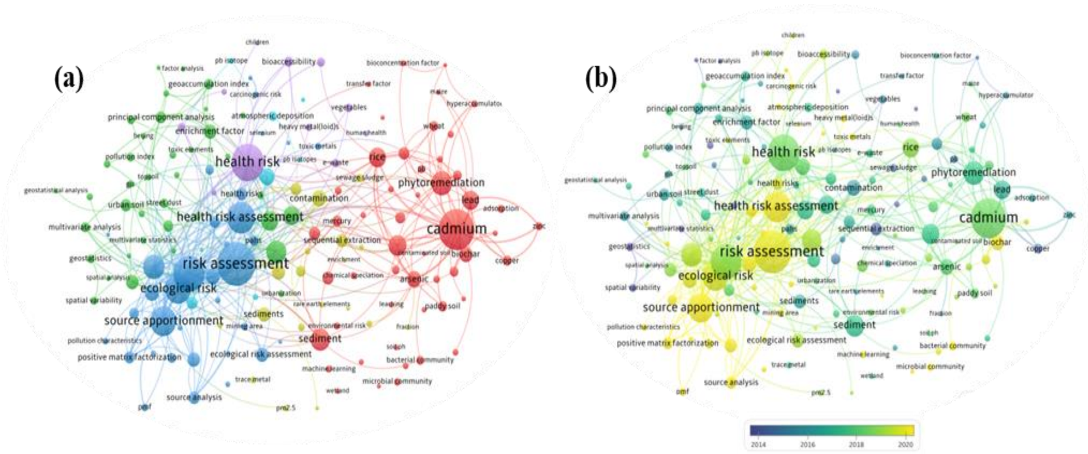

Fig. 1 – Keyword co-occurrence network (a) and time zone map of keywords (b).

The time of the keywords in soil heavy metal research is shown in Fig. 1b, which can reflect the research hotspots and frontiers at a certain stage. 2020–2024, the emerging words are risk assessment, health risk assessment, and source apportionment. This shows that in recent years, this research field has been in a rapid development stage, and researchers have focused more on the harm that heavy metal pollution in soil brings to the surrounding environment and human health.[10]

In China, heavy metal elements, heavy metal pollution in cultivated land, biochar, bioremediation technology and environmental risk assessment are the research hotspots in this field. Recently, health risk assessment and source analysis are the development trends in this field.

Critical Analysis of Heavy Metal Pollution in Roumania

According to the European Environment Agency (EEA), Europe has about 2.5 million potentially contaminated sites, with 340,000 confirmed as contaminated and needing remediation. About 15% have been remediated.[11] The main contamination sources include industrial activities, hazardous waste, pesticide use, and oil spills, with common contaminants being heavy metals, volatile organic compounds, polycyclic aromatic hydrocarbons, and persistent hazardous substances.[12]

As evidenced in Fig. 2, in 2006, the EU proposed a Soil Framework Directive as part of its Thematic Strategy on Soil Protection, but it was never fully implemented. In 2023, the EU proposed a Directive on Soil Monitoring and Resilience (Soil Monitoring Law). The EU Soil Strategy aims for good soil health by 2050 and promotes soil protection, sustainable use, and restoration by 2030. This strategy includes voluntary and legislative actions, and the European Commission will propose a Soil Health Act based on an impact assessment of soil health indicators, monitoring, and sustainable use.[13]

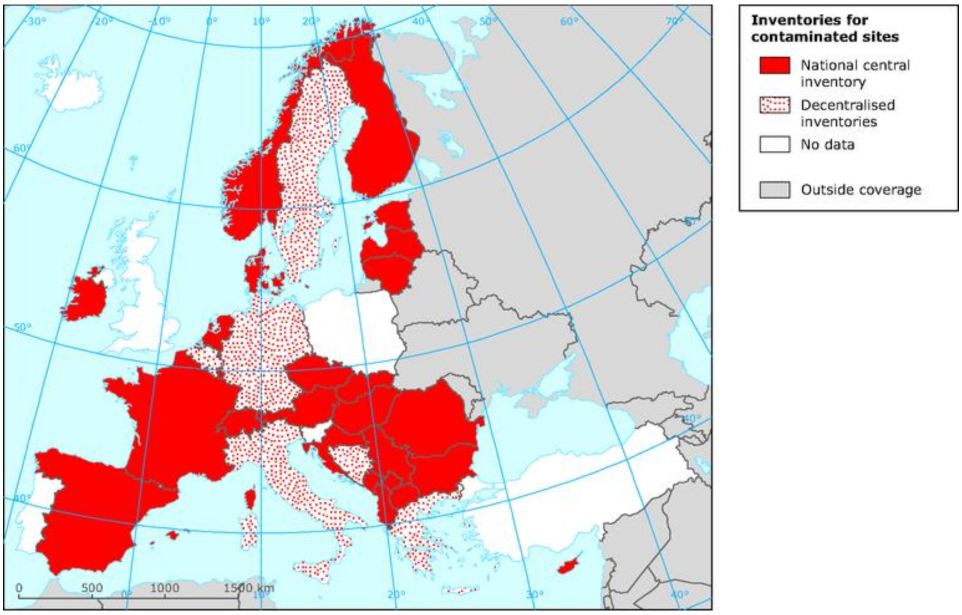

Fig. 2 – Inventories of contaminated/potentially contaminated sites in Europe.[13]

Roumania, the legislation concerning contaminated sites is primarily governed by Law No. 74/2019 covering identification, assessment, remediation, and monitoring.

Soil pollution, caused by human activities, industrial processes, erosion, and urbanization, poses health risks as toxic substances can enter crops and groundwater. Soil can retain hazardous substances due to its properties. Common European soil contaminants include heavy metals and mineral oils, with health risks from arsenic, lead, cadmium, chromium, copper, mercury, nickel, and zinc.[14]

The National Environmental Protection Agency conducted a preliminary inventory of contaminated sites in 2007–2008, categorizing them into potentially contaminated and contaminated sites (Government Decision No. 683/2015).[15]

Fig. 3 – Map of Contaminated and Potentially Contaminated Sites in Roumania.[16]

Heavy metals have been extensively studied in recent years in Roumania (Fig. 3), particularly in heavily polluted areas, due to their significant role in environmental biogeochemical cycles. Past studies in Roumania focused on heavy metals in polluted areas due to their environmental impact. Key contaminated sites include:

Roșia Montană has a long history of gold mining, starting from Roman times. Major open-pit operations began in 1972 but ceased in 2006 due to financial and environmental issues. In 1997, a Canadian joint venture established the Roșia Montană Gold Corporation to reassess the deposits. By 2002, they identified substantial gold and silver resources and planned extraction from four large open pits, including expansion and new, smaller pits. Ore processing was proposed at a nearby plant, with waste rock to be deposited in the Roșia Montană and Corna Valleys, and tailings stored behind a rock dam in the Corna Valley.[17] A 2007 environmental assessment provided Roumanian authorities with data on metal contamination in Roșia Montană. Soil and water samples from residential areas were analyzed to investigate correlations among different metals using SAS statistical software and showed arsenic (85 mg/kg), cadmium (3.2 mg/kg), mercury (2.3 mg/kg), and lead (92 mg/kg) levels exceeding Roumanian limits. Arsenic (25 mg/kg) and mercury (2 mg/kg) surpassed intervention thresholds, while lead (50 mg/kg) and cadmium (3 mg/kg) exceeded alert thresholds. Addressing these environmental concerns is crucial given Roumania's extensive mining history in the Carpathian Mountains.[18]

Copșa Mică is notorious in Roumania for its severe heavy metal pollution, largely attributed to a non-ferrous smelter plant. The entire area is known for its ecological imbalance caused by this industrial activity. In Copșa Mică, industrial activity developed due to local natural gas, water resources, transportation routes, and labor. In 1937, the Canal Nr. 2 Carbon Black Factory was built, followed by the Formaldehyde Factory in 1940, which began operating in 1941. This chemical plant was the first of its kind in Roumania, with a unique process worldwide.[19] Investigations revealed significant lead and cadmium contamination in Copșa Mică's soil and surroundings. High heavy metal levels in plants and food products pose serious health risks. Lead concentrations were highest in nearby soil samples, and cadmium levels exceeded limits near the pollution source.[20]

Baia Mare gained worldwide attention after a major cyanide spill from a gold mine on January 30, 2000, released 100,000 cubic meters of contaminated water into Roumania's Lapus River, affecting Hungary, Yugoslavia, and the Black Sea. A second incident on March 10, 2000, when Baia Borșa mining company's settling pond dam broke, released 20,000 tonnes of heavy metal-laden slurry into the same rivers. Studies found excessive metal concentrations in surface soils, surpassing Roumanian legal limits.[21] Previous studies found that surface soils contain excessive concentrations of metals surpassing the limits set by Roumanian law.

In conclusion, Roumania faces the heavy legacy of an intense extractive and metallurgical industry, which has left behind sites contaminated with heavy metals. Remediation and environmental protection efforts are essential to minimize the impact on human health and affected ecosystems in these areas.

Critical Analysis of Air Pollution in Rwanda

In Rwanda, vehicle emissions significantly contribute to urban air pollution, posing serious health risks. These pollutants also cause environmental issues like acid rain, global warming, climate change, and weather variability. Despite efforts to reduce emissions, air pollution from various sources, including industry, agriculture, and household activities, remains a concern.[22]

$PM_{2.5}$ and PM_{10} particulate matter originate from vehicle emissions, industrial activities, construction, agricultural burning, and residential cooking and heating. Sulfur dioxide (SO_2) is primarily released from burning fossil fuels in power plants, industrial processes, and vehicle emissions. Nitrogen dioxide (NO_2) emissions come from vehicles, power plants, and industrial activities. Ground-level ozone (O_3) is not emitted directly but forms through reactions between NO_2 and volatile organic compounds (VOCs) in the presence of sunlight.[23]

These pollutants have severe effects on human health. $PM_{2.5}$ and PM_{10} can infiltrate deep into the lungs and enter the bloodstream, leading to respiratory and cardiovascular problems, such as asthma, bronchitis, heart attacks, and early death. Exposure to SO_2 can cause respiratory issues, including asthma and bronchitis, and worsen pre-existing heart conditions. It also contributes to the creation of particulate matter in the air. Breathing in NO_2 can irritate the respiratory tract, reduce lung function, and elevate the risk of respiratory infections. Long-term exposure can lead to the development of asthma and other respiratory conditions. Ground-level ozone can cause respiratory problems, worsen asthma, decrease lung function, and result in more hospital visits and early deaths. It also harms vegetation and ecosystems.[24]

The region's geography influences atmospheric patterns and the dispersion of these pollutants. The relationship between topography and pollutant distribution is complex, involving factors like wind speed, direction, temperature, and atmospheric stability. Urban areas with diverse landscapes-such as mountains, hills, and valleys, and ridges-experience varied dispersion patterns. Air rising over these features cools, creating clouds and precipitation that deposit pollutants while descending air warms and disperses them. This results in complex pollutant distribution patterns, impacting health and the environment.[25]

A critical analysis of air pollution in Rwanda underscores the need for comprehensive strategies to manage emissions of $PM_{2.5}$, PM_{10}, SO_2, NO_2, and O_3 from multiple sources. Addressing the challenges posed by the region's unique topography is crucial. Effective pollution control measures must consider the complex interaction between geographical features and pollutant dispersion to mitigate health risks and environmental impacts.

Critical Analysis of Mps in Air and Soil in Roumania

Mps are very small plastic particles, less than 5 mm in size,[26] from various sources, including the breakdown of larger plastic items and consumer products such as cosmetics and synthetic clothing.

Air pollution by Mps is a growing global concern with significant impacts on human health and ecosystems. Major sources of airborne Mps include *(i)* the decomposition of larger plastics, *(ii)* the abrasion of tires and synthetic textiles, and *(iii)* industrial and agricultural activities. In addition, the burning of waste, especially that containing plastic, contributes significantly to the dispersion of these particles in the atmosphere. Mps can spread over long distances due to their small size, becoming a global problem. Studies have shown that Mps can contain and transport dangerous chemicals and microbes, raising concerns about their impact on organism's respiratory health and immune systems.[4]

In Roumania, Mps air pollution is becoming increasingly visible, although specific research is still being developed. The main sources of Mps in the air include heavy road traffic,[27] abrasion of tires and braking systems, and uncontrolled waste burning,[28] including plastic. Also, industrial and agricultural activities contribute to the dispersion of Mps in the air. In the urban environment, heavy road traffic and frequent use of motor vehicles generate significant Mps.[29,30] Abrasion of tires and braking systems releases fine plastic particles into the atmosphere, which can be inhaled by humans and animals.[31]

In addition to the mentioned sources, agricultural activities also play an important role in the dispersion of Mps. The use of plastic materials in agriculture [32], such as plastic sheets for mulching and irrigation,[33] contributes to the release of Mps into the air. In rural areas, uncontrolled burning of waste, including plastic waste,[34] is a major source of Mps pollution. These particles can reach the lungs by inhalation and can affect human health,[35,36] although exact research on their health impact in Roumania is still limited. Increased research is crucial to better understand the mechanisms by which Mps affect health and to identify effective measures to reduce exposure.

Furthermore, the implementation of effective measures to monitor and reduce Mps air pollution in the specific context of the country is essential. Authorities should invest in air quality monitoring infrastructure, more strictly regulate waste management, and promote sustainable alternatives to plastics. Educating the public on the impact of Mps and methods to reduce pollution is also an important aspect of the solution.[37] By comprehensively addressing this problem, Roumania can take important steps toward protecting public health and the environment from the harmful effects of Mps pollution.[38]

According to Institutul Național de Sănătate Publică,[39] the phenomenon of soil pollution with Mps is a topic of current and increasing importance.

Sources of Mps in Soil: Mps reach soil[40] from a variety of sources. These include plastic waste that breaks down over time, sewage sludge used as fertilizers, particles from tire abrasion, and the wear and tear of synthetic materials.[41] There are also significant contributions from other anthropogenic sources such as agricultural practices and industrial waste.[42–44] This section will examine each of these sources in detail and how they contribute to soil contamination.

Mechanisms of transport and dispersion: Mps are transported and dispersed in soil[45] by various mechanisms: *(i)* Irrigation water[46] and precipitation can transport Mps into the soil, while *(ii)* agricultural activities[47] and *(iii)* wind can contribute[48] to their surface dispersion. Also, Mps can migrate both vertically and horizontally in the soil, affecting different layers and regions. They have a significant impact not only on the environment but also on health. In soil, they can affect structure and fertility by interacting with other contaminants such as heavy metals.[49] Soil flora and fauna may suffer adverse effects, and bioaccumulation of these particles may lead to risks to human health, particularly through the food chain. The link between soil Mps and heavy metals is a complex environmental problem. Mps not only pollute the environment through their physical presence but also act as vectors for heavy metals, amplifying pollution and associated risks. The studies emphasize the need for rigorous management of plastic waste and measures to reduce soil contamination to lessen these negative effects.

Soil pollution in Roumania is a serious problem,[50] with numerous examples illustrating various types of contamination. Here are some notable examples: *(i) Heavy metal pollution in Baia Mare/* Baia Mare, a city known for its mining and metallurgical activities, has been severely affected by soil pollution with heavy metals such as lead, zinc, and cadmium. In 2000, a massive cyanide leak from the Aurul company contaminated the Tisa River,[51] affecting both the area's soils and aquatic ecosystems;[52] *(ii) Pesticide pollution in agricultural areas/* many agricultural regions in Roumania,[53] the intensive use of pesticides and chemical fertilizers has led to soil contamination. Especially in the southern counties of the country, such as Teleorman and Giurgiu, soils are affected by persistent pesticide residues, which can negatively influence water quality and human health; *(iii) Industrial waste in Ploiești/* Ploiești, an important industrial center, faces soil pollution due to waste from petroleum and chemical activities.[54]

Oil residues and other toxic substances have seeped into the soil, affecting its quality and posing a health risk to residents. *(iv) PCB (polychlorinated biphenyls) contamination in Copșa Mică*/Copșa Mică was one of the most polluted cities in Europe,[55] mainly due to industrial activities of metal processing and carbon black production. Pollution with (PCBs) and other toxic substances has affected the soils around the factories, hurting the health of the population and the environment. *(v) Illegal waste dumps in Ilfov and Bucharest/* In the areas near Bucharest and in Ilfov county, the illegal storage of household and industrial waste has led to soil contamination.[56] Many of these wastes contain hazardous substances that seep into the soil, affecting both soil quality and groundwater. *(vi) Mps pollution in urban and rural areas* Mps has become an emerging problem in Roumania as well.[57] In urban areas, Mps from tire abrasion, plastic wear, and household waste contaminate soils. In rural areas, the use of sewage sludge[58] and contaminated fertilizers contributes to soil pollution with Mps. These examples illustrate various types of soil pollution in Roumania and underline the need for effective measures to protect the environment and remediate contaminated soils.

CONCLUSIONS

The critical analysis of particle and gaseous pollutants, Mps, and heavy metal pollution in Rwanda, Roumania, and China highlights significant environmental challenges in each country. Each country faces severe pollution issues with different sources, levels of contamination, and regulatory responses.

In Rwanda, rapid urbanization and industrialization have increased particle and gaseous pollutants, especially in urban areas, with biomass use for cooking contributing significantly. Rwanda has made progress in reducing emissions and promoting renewable energy. Roumania struggles with pollution from industrial activities, leading to significant heavy metal contamination in soil and water. EU integration has prompted stricter environmental regulations, but enforcement and compliance need improvement. China faces severe soil heavy metal pollution, focusing on biochar, bioremediation, and environmental risk assessment. China is actively using biotechnology and passivation materials to remediate soil pollution. Addressing these challenges requires stronger regulatory frameworks, better enforcement, and investment in cleaner technologies. Public awareness, education campaigns, research, and innovation are crucial across all three countries. Enhancing waste management systems and promoting sustainable practices will further reduce environmental impacts, with international cooperation addressing transboundary pollution.

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