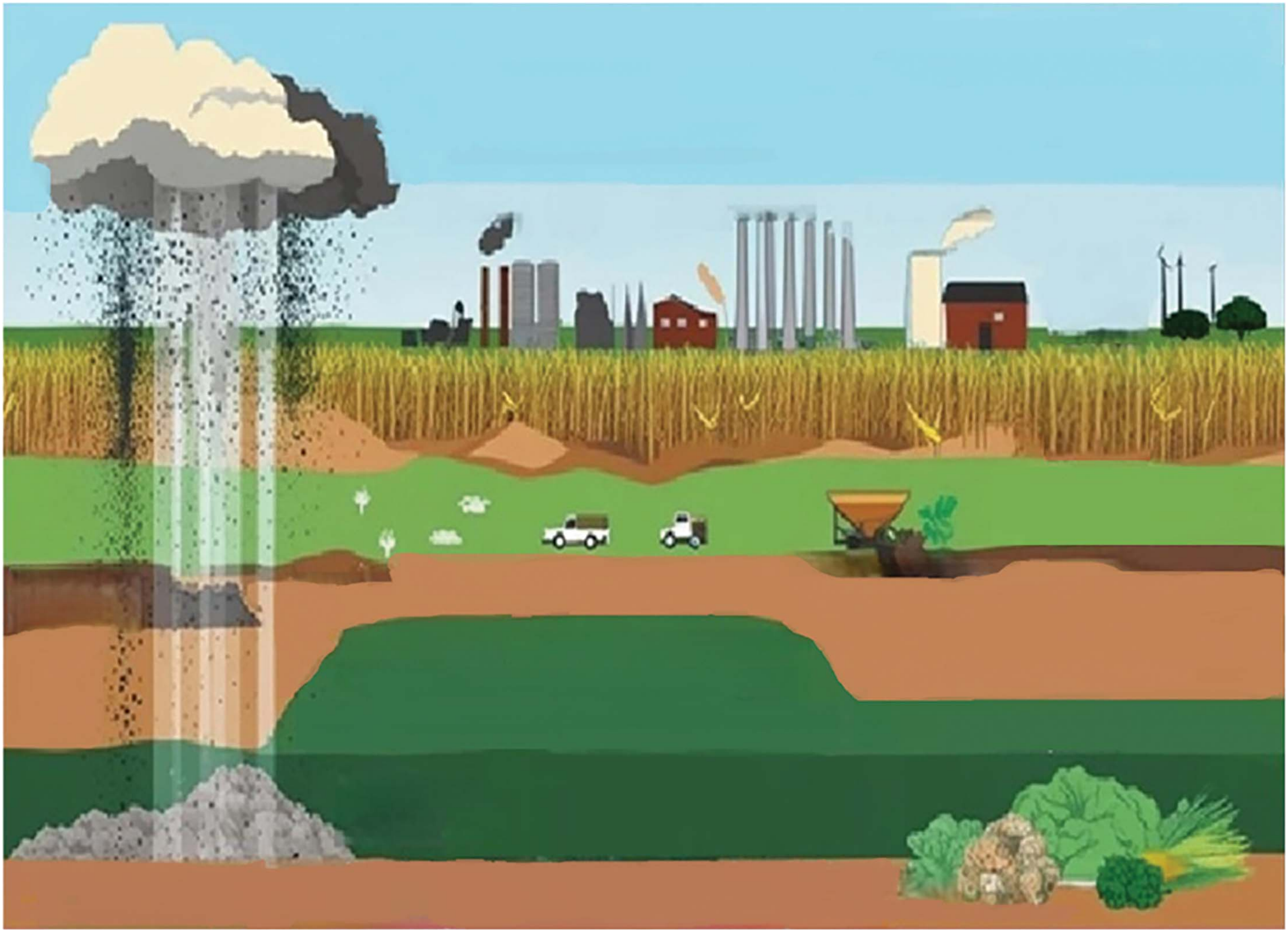

Showcasing research from Dr. Zikfullah Safi's laboratory, Department of Plant Production and Agroecosystem Research in the Tropics and Subtropics, University of Kassel, Germany.

A systematic review of wet and dry deposition of reactive nitrogen, sulfur, and heavy metals: ecosystem contamination and food chain disruption in Ghana

This graphical abstract summarizes key findings on environmental contamination in Ghana, highlighting major pollutant emission sources including agriculture, vehicular traffic, and industrial activities. The image illustrates how these sources contribute to patterns of atmospheric pollutant deposition across different regions. The artwork was created and edited by the authors using Canva and Paint. This cover highlights the urgent need for targeted environmental policies to manage emissions and protect air quality in Ghana, contributing to a deeper understanding of pollution dynamics in developing countries.

Image reproduced by permission of Zikrullah Safi from *Environ. Sci.: Atmos.*, 2025, **5**, 756.

As featured in:

Environmental Science Atmospheres

See Zikrullah Safi *et al.*, *Environ. Sci.: Atmos.*, 2025, **5**, 756.

ROYAL SOCIETY OF CHEMISTRY

rsc.li/esatmospheres

Environmental Science: Atmospheres

ROYAL SOCIETY OF CHEMISTRY

CRITICAL REVIEW

View Article Online
View Journal | View Issue

Check for updates

Cite this: *Environ. Sci.: Atmos.*, 2025, **5**, 756

A systematic review of wet and dry deposition of reactive nitrogen, sulfur, and heavy metals: ecosystem contamination and food chain disruption in Ghana

Zikrullah Safi, *[a] Michael Miyittah,[b] Benjamin Kwasi Offei[c] and Godwin Amenorpe[c]

Environmental contamination in Ghana, driven by dust deposition, particulate matter (PM), reactive nitrogen, sulfur, and heavy metals, poses significant risk to public health and the environment. However, comprehensive assessments of the spatial distribution and seasonal variations of these pollutants remain limited. To address this gap, this study synthesizes data from 68 site-specific studies conducted between 1997 and 2024. Our findings reveal substantial regional disparities in contamination levels. During the Harmattan season, the Northern region accounted for 52% of total dust deposition, while the Central and Southern regions contributed 12% and 37%, respectively. The Central region exhibited the highest concentrations of PM, with median values of PM2.5 (489 μg m^{-3}), PM10 (703.5 μg m^{-3}), and TSP (710.5 μg m^{-3}). Heavy metal contamination in agricultural products was particularly concerning, with cocoa showing elevated levels of copper (48.67 mg kg^{-1}), lead (70.03 mg kg^{-1}), and iron (41.60 mg kg^{-1}). Fish samples revealed high lead (5.97 mg kg^{-1}) and iron (156.39 mg kg^{-1}). Lettuce and onions demonstrated moderate contamination with lead and cadmium. In mining regions such as Obuasi, lead and arsenic concentrations exceeded WHO safety limits. Sulfur deposition was notably high in Southern Ghana, constituting 81.4% of airborne pollutants. Rainwater contamination, primarily from sulfate, contributed to acidic rainfall (pH < 6.5) in the Southern and Central regions. These findings underscore the urgent need for targeted interventions, particularly in mining and urban areas. Implementing stronger pollution control measures, enhancing monitoring systems, and developing specific strategies to mitigate risks to public health and agriculture are critical steps toward addressing these environmental challenges.

Received 4th February 2025
Accepted 10th June 2025

DOI: 10.1039/d5ea00018a

rsc.li/esatmospheres

Environmental significance

This systematic review reveals the critical role of atmospheric wet and dry deposition of reactive nitrogen, sulfur, and heavy metals in shaping ecosystem health and food chain contamination in Ghana. Our findings highlight substantial spatial and seasonal disparities in pollutant deposition, with notable peaks during the Harmattan season. The study underscores the urgent need for targeted interventions in agricultural, industrial, and urban areas to mitigate pollutant deposition and safeguard public health, biodiversity, and food security.

1. Introduction

The deposition of reactive nitrogen, sulfur, and heavy metals in the environment, primarily from anthropogenic sources, poses significant risks to ecosystems and public health. This is particularly true in developing countries such as Ghana, where industrial processes, agricultural activities, and vehicular emissions are major contributors. These pollutants not only impact human health but also influence biogeochemical cycles, thereby affecting ecosystem health and functioning.

Aeolian dust deposition is particularly important in Ghana's environmental context. This process introduces foreign minerals and organic materials which contribute to nutrient cycling, soil fertility, and overall ecosystem health. Dust deposition also affects vegetation and soil microbial processes.[1–3] Globally, dust deposition rates vary widely, with values exceeding 450 g per m^2 per year in some regions, highlighting the substantial regional differences in ecosystem impacts.[1]

Urban and peri-urban areas face significant challenges from pollutants such as heavy metals and reactive nitrogen

---

[a] *Organic Plant Production and Agroecosystems Research in the Tropics and Subtropics, Faculty of Organic Agriculture, University of Kassel, 37213 Witzenhausen, Germany. E-mail: zikrullah.safi@uni-kassel.de; zikprosafi@gmail.com; Tel: +49 151 17876819*

[b] *Department of Environmental Science, University of Cape Coast, University Avenue, North Campus, Cape Coast, Ghana*

[c] *Biotechnology and Nuclear Agriculture Research Institute, Ghana Atomic Energy Commission, Legon-Accra, Ghana*

compounds. These pollutants enter ecosystems through dust, precipitation, and irrigation water, primarily originating from industrial emissions, vehicular emissions, and agricultural practices. Heavy metals (*e.g.*, lead, cadmium, and arsenic) are especially concerning due to their toxicity, persistence, and potential for bioaccumulation in the food chain. Elevated levels in crops such as arsenic in rice (0.36 mg kg^{-1}) and lead in lettuce (up to 5.18 mg kg^{-1}) pose substantial health risks.[4–6] Long-term exposure can cause neurotoxic effects, liver and kidney damage, and disruption of soil microbiota, ultimately threatening agricultural productivity.[7,8]

Urbanization and rural-urban transformation in Ghana have significantly altered land use and agricultural practices.[9,10] Increasing market demand has driven agricultural intensification,[11,12] leading to increased fertilizer and agrochemical use. These inputs contribute to soil over-fertilization, nitrogen leaching, and greenhouse gas emissions. Wet deposition of reactive nitrogen further enriches soils, leading to acidification, eutrophication, and increased emissions. These changes raise public health concerns particularly for vulnerable populations by increasing risks of methemoglobinemia (blue baby syndrome) and gastrointestinal diseases.[13–16]

Despite growing awareness of these challenges, significant knowledge gaps remain regarding the specific effects of wet and dry deposition of reactive nitrogen, sulfur, and heavy metals on ecosystems and food chains in Ghana. Studies from Central Ghana, Accra, and Ashaiman report variations in particulate matter levels, especially during the Harmattan season, driven by both long-range aerosol transport and local pollution sources.[17–19] Industrial activities (*e.g.*, e-waste sites) and poor waste management have elevated lead, copper, and other toxic metals in soil and groundwater.[20–22]

This systematic review synthesizes existing research on the deposition of reactive nitrogen, sulfur, and heavy metals in Ghana, focusing on impacts on ecosystem health, food safety, and agricultural productivity. Based on 68 site-specific studies conducted between 1997 and 2024, we analyze dust deposition rates, pollutant distribution patterns, and their implications for local ecosystems. The findings aim to inform policy and management strategies that address pollution in urban and peri-urban agricultural areas, ultimately supporting sustainable agricultural practices and enhancing food safety nationwide.

The objectives and research questions:

Objectives:

(1) Assess current dust and particulate matter deposition rates across Ghana.

(2) Analyze the distribution of reactive nitrogen, sulfur, and heavy metals from dust, rainfall, and airborne deposition.

(3) Identify the main sources and environmental pathways through which these pollutants enter Ghanaian ecosystems.

(4) Evaluate their effects on ecosystem functioning, crop productivity, and food safety.

(5) Recommend policies and management strategies to mitigate pollution and support sustainable agricultural practices.

Research questions:

(1) What are the current rates of dust and particulate matter deposition across Ghana?

(2) How do the distribution patterns of reactive nitrogen, sulfur, and heavy metals differ across urban and agricultural environments?

(3) What are the main sources and transport pathways of these pollutants?

(4) How do these pollutants affect ecosystem functioning, agricultural productivity, and food safety?

(5) What gaps exist in the literature on wet and dry deposition in Ghana?

(6) How can these findings inform policy and management strategies for sustainable agriculture?

By addressing these questions, this review aims to provide critical insights for researchers, policymakers, and environmental managers to develop effective strategies for pollution mitigation and ecosystem protection.

2. Materials and methods

This systematic review was conducted following PRISMA 2020 guidelines to ensure transparency and rigor. The methodology included four main steps: literature search, eligibility screening, data extraction and data analysis.

2.1 Literature search strategy

A systematic literature search was conducted across multiple electronic databases (Google Scholar, PubMed, Web of Science, Scopus, and JSTOR), covering publications from 1997 to 2024. The search focused on aeolian dust and the wet and dry deposition of reactive nitrogen, sulfur, and heavy metals, both globally and within Africa. Keywords included: aeolian dust, particulate matter, wet deposition, dry deposition, reactive nitrogen, sulfur, heavy metals, urban agriculture, ecosystem contamination, and food chain disruption. Boolean operators (AND and OR) refined the search. A total of 940 articles were initially identified. After removing duplicates and screening titles, abstracts, and full texts for relevance, 68 site-specific articles were retained. Fig. 1 presents the PRISMA flow diagram illustrating the selection process.

2.2 Inclusion and exclusion criteria

Studies published in English between 1993 and 2024 that focused on Ghanaian surfaces (Fig. 2) and provided quantitative data on pollutant deposition or ecosystem/food system impacts were included. Studies were excluded if they predated 1993, were not peer-reviewed, did not examine ecosystem or food chain contamination, or lacked relevant quantitative measurements.

2.3 Data extraction and synthesis

Data extracted included author(s), year of publication, study location, pollutant type, and study context (urban/agricultural). These data were compiled into summary tables (Tables 5–10) to facilitate cross-study comparison.

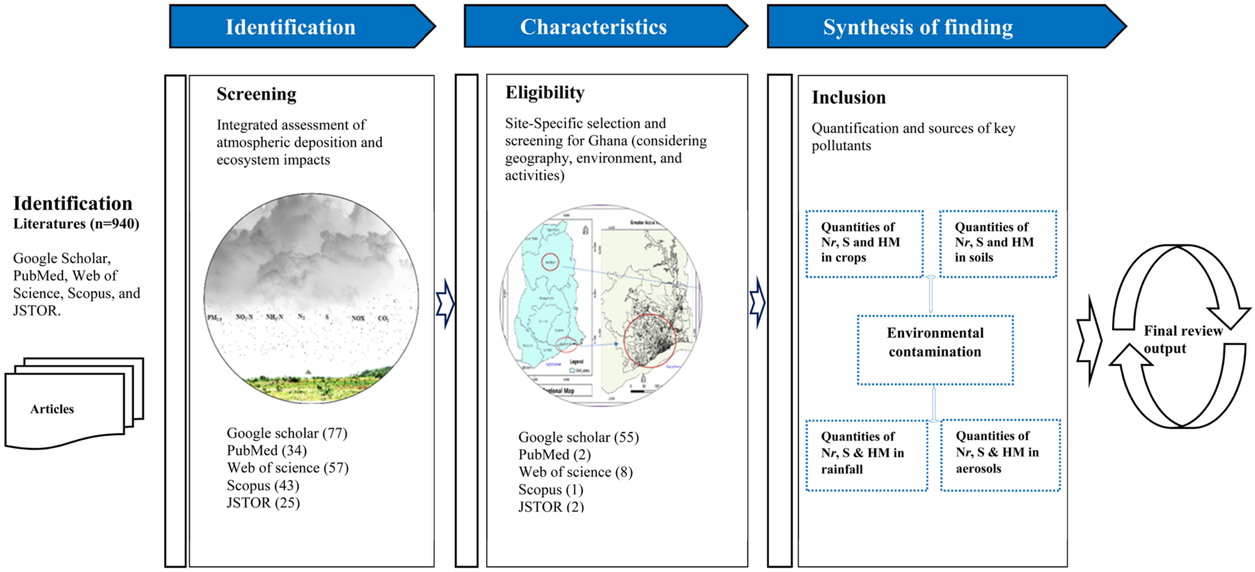

Fig. 1 PRISMA flowchart illustrating the literature screening and selection process for the systematic review on aerosol deposition, including reactive nitrogen (Nr), sulfur (S), and heavy metals (HMs) in Ghana. A total of 68 peer-reviewed articles met the inclusion criteria and were incorporated into the final synthesis.

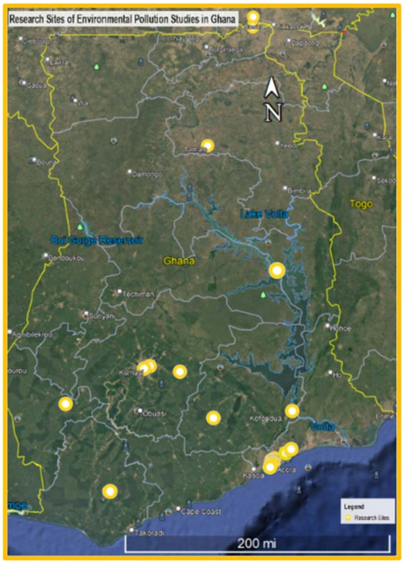

Fig. 2 Map of Ghana showing the approximate locations of research sites included in this review. Due to data limitations, only a subset of the 68 identified sites is displayed. The base map was created using Google Earth Pro.

2.4 Data analysis and reporting

The study selection process was documented using a PRISMA flow diagram,[23,24] illustrating the number of records identified, included, and excluded during the screening process. Summary tables were created to organize and present key findings, facilitating comparisons across studies.

For the quantitative synthesis, a meta-analysis approach was applied to aggregate data on pollutant deposition rates across different geographic regions. Descriptive statistics such as the mean, median, and standard deviation were calculated to summarize the data. Depending on data distribution, appropriate statistical models were selected. For normally distributed data, parametric models were applied using SPSS version 23.0 (SPSS Inc., Chicago, IL, USA).[25] For non-normally distributed data, non-parametric models were used to ensure accurate analysis based on the data characteristics. Statistical significance was set up at $p < 0.05$.

3. Results

3.1 Chronological record of dust deposition across geographical regions of Ghana

Our key findings from dust deposition studies conducted between 1993 and 2022 in Ghana show significant regional and seasonal variations, particularly during the Harmattan season (November to March). Northern Ghana consistently experiences higher rates of dust deposition compared to the southern regions. For instance, during the 2001–2002 Harmattan season, dust deposition rates varied from 25 g m^{-2} in Bawku, 16 g m^{-2} in Tamale, and 5 g m^{-2} in Sefwi Bekwai.[2] Similarly, the 2002–2006 period demonstrated a stark difference, with dust deposition rates of 160 kg ha^{-1} in the north, gradually declining to approximately 60 kg ha^{-1} in the south.[3] In Kade, an average dust deposition rate of 13.53 g m^{-2} was recorded over three Harmattan seasons.[25] These findings highlight significant regional differences and the strong influence of seasonal dust transport, particularly during the Harmattan season.

Recent studies continue to show variability in dust deposition across different regions. For example, Emetere *et al.*[26] and Adu-Gyamfi *et al.*[27] reported fluctuations in atmospheric aerosol retention in Bolgatanga, with levels peaking at 64.27 mg m^{-2} in 2012. Additionally, Awuah *et al.*[28] observed a monthly average of 60.2 g m^{-2} near cement factories in southern Ghana. While this section highlights key findings from selected studies, readers can refer to Table 5 for a comprehensive overview of dust deposition data from 1993 to 2022. These findings underscore the considerable influence of regional and seasonal factors on dust deposition patterns in Ghana, particularly during the Harmattan season.

3.1.1 Meta-analysis of regional variations in dust deposition during the Harmattan season in Ghana. We conducted a meta-analysis on the findings from eight out of ten studies (Table 5) focused on dust deposition during the Harmattan season (November to March), selected for their consistency and relevance. To enable comparison, all data were harmonized to g m^{-2} for consistency with the narrative section. Long-term and short-term averages were applied where necessary to standardize the data.

Data analysis was performed using univariate analysis of variance (ANOVA) using SPSS. The results, shown in Fig. 3, indicate significant regional variations in dust deposition during the Harmattan season: the North contributed 52% of the total deposition, the Central region accounted for 12%, and the South represented 37%. Although the ANOVA did not reveal statistically significant regional differences ($p = 0.406$), the North displayed the highest deposition rates, highlighting variability in dust deposition across Ghana. Notably, data on dust deposition in the Southwest region are unavailable, indicating a significant gap in the literature that warrants further investigation.

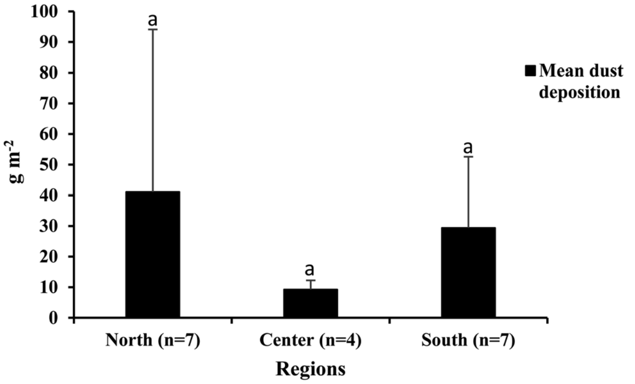

Fig. 3 Regional variations in dust deposition during the Harmattan season in Ghana. Bars with the same letter indicate no significant differences ($p = 0.406$).

3.2 Chronological records of particulate matter deposition in Ghana

Particulate matter (PM) deposition in Ghana is significantly influenced by local environmental conditions and seasonal variations, particularly during the Harmattan season. Between 1997 and 2022, substantial seasonal fluctuations in PM concentrations were observed, with higher levels recorded during the Harmattan period (January–March), primarily due to Saharan dust intrusions. Studies such as Sunnu *et al.*[17] highlighted notable PM concentrations across Central Ghana, with PM2.5, PM5, and PM10 averaging 599 μg m^{-3}, 598 μg m^{-3}, and 1037 μg m^{-3}, respectively, during the Harmattan period. Total suspended particles (TSP) averaged 1069 μg m^{-3}. These findings align with other studies in Accra and Kumasi (*e.g.*, Aboh & Ofosu[18,29,30]), which also documented seasonal peaks during the Harmattan season, with PM concentrations exceeding WHO air quality guidelines in several locations.

Recent studies (*e.g.*, Krampah *et al.*[31] and Alli *et al.*[17]) continue to report elevated PM concentrations during the dry Harmattan months. For instance, in Accra, PM2.5 concentrations have reached as high as 89 μg m^{-3}, with localized spikes during periods of heavy traffic and dust storms. More recent measurements by Bahino *et al.*[32] and Gyasi *et al.*[33] confirm sustained high particulate levels during the Harmattan season, with concentrations reaching an air quality index (AQI) of 204 μg m^{-3} in Cantonments, a densely populated area in Accra. While this section highlights key findings from selected studies, readers can refer to Table 6 for a comprehensive overview of particulate matter deposition data from 1997 to 2022.

3.2.1 Meta-analysis of particulate matter deposition in Ghana. A meta-analysis was conducted on particulate matter (PM) deposition data across Ghana from 1997 to 2022 (Table 6), incorporating data from fourteen studies standardized for statistical comparison across regional groupings. The regions were grouped as Central, Southern, and Southwest for the analysis of PM concentrations (PM2.5, PM10, and TSP) during both the Harmattan and non-Harmattan seasons. The comparison of means was performed using the compare means procedure in SPSS software.

The results revealed the highest Grouped Median Concentrations (GMCs) of PM during the Harmattan season in the Central region, with GMC values of 489.00 μg m^{-3} for PM2.5, 703.50 μg m^{-3} for PM10, and 710.50 μg m^{-3} for TSP (Table 1). In contrast, the Southern and Southwest regions exhibited comparatively lower

Table 1 Grouped median concentrations (GMCs) of particulate matter (PM2.5), (PM10), and total suspended dust particles (TSP) during Harmattan and non-Harmattan periods across regions

		Harmattan			Non-Harmattan[a,b]		
Regions		$PM_{2.5}$ (μg m^{-3})	PM_{10} (μg m^{-3})	TSP (μg m^{-3})	$PM_{2.5}$ (μg m^{-3})	PM_{10} (μg m^{-3})	TSP (μg m^{-3})
Central	GMC	489.00	703.50	710.50			
Southern	GMC	89.00	119.45	370.00	22.25	72.72	75.12
Southwest	GMC	27.00	56.70	113.20	27.00	39.70	80.30

[a] Harmattan: (November to March). [b] Non-Harmattan: (April to October).

deposition rates, particularly during the non-Harmattan periods. The Southern region recorded GMCs of 89.00 μg m^{-3} (PM2.5), 119.45 μg m^{-3} (PM10), and 370.00 μg m^{-3} (TSP) during the Harmattan season. The Southwest region demonstrated relatively stable particulate concentrations across both seasons, with median values of 27.00 μg m^{-3} for PM2.5, 56.70 μg m^{-3} for PM10, and 113.20 μg m^{-3} for TSP during the Harmattan, with similar concentrations observed during the non-Harmattan period.

3.3 Chronological records of environmental media (soil and water) contamination across Ghana

Between 2008 and 2024, multiple studies have highlighted significant contamination of environmental media (water, soil, and dust) by reactive nitrogen, sulfur, and heavy metals across Ghana (Table 7). Urban and peri-urban areas, such as Kumasi and Accra, have seen high concentrations of heavy metals such as lead, arsenic, and cadmium, often exceeding recommended limits. For example, in Kumasi, Kodum *et al.*[34] reported elevated levels of arsenic (18.6 mg kg^{-1}), lead (571.3 mg kg^{-1}), and zinc (908.6 mg kg^{-1}), while Obiri-Nyarko *et al.*[35] found high concentrations of lead (351.67 mg kg^{-1}) and zinc (1875.67 mg kg^{-1}) at the Kpone landfill site. In Accra, a 2022 study by Edusei *et al.*[36,37] found concerning levels of aluminum (82 300 ppm), silicon (281 500 ppm), and iron (56 300 ppm) in soil, although lead and copper levels were somewhat lower. Mining regions, such as Obuasi and Kenyasi, have also reported persistent

Table 2 Regional distribution of heavy metal (arsenic (As), copper (Cu), lead (Pb), zinc (Zn), cadmium (Cd), manganese (Mn), and iron (Fe)) contamination in the environment (soil and water) across Ghana

Region	Element	*N* (soil)	Soil median (mg kg^{-1})	Soil SE (mg kg^{-1})	*N* (water)	Water median (mg L^{-1})	Water SE (mg L^{-1})	Threshold values mg kg^{-1}	Threshold values mg L^{-1}	Remarks[d]
North	As	NA[a]	NA	NA	NA	NA	NA	5.00[c]	0.01	No data available
	Cu	NA	NA	NA	NA	NA	NA	100[c]	2.00	No data available
	Pb	NA	NA	NA	1.00	0.02	NA	60.0[c]	0.01	Higher lead contamination observed in water
	Zn	NA	NA	NA	NA	NA	NA	200[c]	3.00	No data available
	Cd	NA	NA	NA	1.00	0.02	NA	1.00[c]	0.003	Cadmium concentration in water exceeds safety limits
	Mn	NA	NA	NA	NA	NA	NA	—	0.1[b]	No data available
	Cr	NA	NA	NA	2.00	15.35	0.96	100[c]	0.05	Chromium levels in water are significantly high
	Fe	NA	NA	NA	3.00	0.99	0.48	—	—	Within the aesthetic threshold limit for iron in water
South	As	6.00	5.60	28.07	NA	NA	NA			Highest arsenic levels in soil were observed in this region
	Cu	3.00	79.9	165.10	NA	NA	NA			Copper contamination in soil is notably high
	Pb	7.00	24.2	90.46	3.00	0.03	0.00			Elevated lead levels in both soil and water
	Zn	3.00	908.6	506.56	NA	NA	NA			Zinc concentration in soil is significantly high
	Cd	1.00	6.3	NA	2.00	0.00	0.00			High cadmium concentration detected in soil
	Mn	1.00	228.2	NA	NA	NA	NA			Moderate levels of manganese observed in soil
	Cr	2.00	310.6	235.18	NA	NA	NA			Chromium levels in soil are the highest among this region
	Fe	1.00	56 300	NA	1.00	0.30				The highest crustal iron levels were observed in soil
South west	As	NA	NA	NA	4.00	0.01	0.01			Arsenic concentration in water is low
	Cu	1.00	33.39	NA	NA	NA	NA			Copper levels in soil are low
	Pb	1.00	57.91	NA	3.00	0.05	0.02			Low lead in both soil and water
	Zn	1.00	70.06	NA	NA	NA				Zinc concentration in soil is relatively low
	Cd	1.00	0.16	NA	2.00	0.00	0.00			Low levels of cadmium detected in soil
	Mn	1.00	5206.42	NA	NA	NA	NA			Manganese concentration in soil is the highest recorded
	Cr	1.00	47.34	NA	NA	NA	NA			Chromium levels in soil are low
	Fe	NA	NA	NA	NA	NA	NA			No data available

[a] Notes: NA: not available/not applicable. [b] Mn levels >0.1 mg L^{-1}: May cause bad taste and discoloration in water. [c] Threshold values, source.[40,41] [d] Remarks: based on exceeding critical concentration limits.

contamination due to intensive mining activities, with arsenic (7.31 mg kg^{-1}) and cadmium (17.32 mg kg^{-1}) found at harmful concentrations. The deposition of reactive nitrogen and sulfur is also significant, with nitrogen and sulfur compounds identified as major contributors to pollution in both urban and agricultural areas. Elevated levels of nitrogen compounds, such as nitrate and ammonium, have been observed in water and soil samples, often linked to agricultural runoff and industrial emissions. A study by Bessah *et al.*[38] identified lead contamination (18.73 μg L^{-1}) in the Pra River Basin, well above safety thresholds. Similarly, Asamoah *et al.*[39] observed heavy metal contamination, including arsenic (175.14 mg kg^{-1}) and cadmium (6.30 mg kg^{-1}) in Obuasi, reflecting the persistent environmental pollution from mining and industrial activities.

3.3.1 Meta-analysis of regional variation in environmental media (soil and water) contamination across Ghana. After applying inclusion and exclusion criteria, 16 out of 28 environmental pollution studies (Table 7) were selected for meta-analysis. Measurement units were harmonized, and data were summarized using SPSS with grouped median values (GMVs). Studies reporting concentrations above established threshold limits were prioritized, while data below threshold limits or marked as "NA" (not available/not detected) were excluded.

The results show significant regional variation in contamination levels, with data for the Central region unavailable. In the Northern region, the grouped median concentrations for lead (Pb) and cadmium (Cd) in water were 0.02 mg L^{-1}, and nitrate (NO_3) in soil had a median of 15.35 mg L^{-1}. In the Southern region, arsenic (As) in soil had a median of 5.60 mg kg^{-1}, with copper (Cu) and zinc (Zn) at 79.9 mg kg^{-1} and 908.6 mg kg^{-1}, respectively. Lead (Pb) contamination in soil was 24.2 mg kg^{-1}, and cadmium (Cd) was 6.3 mg kg^{-1}. In the Southwestern region, manganese (Mn) in soil had a median of 5206.42 mg kg^{-1}, while copper (Cu) has 33.39 mg kg^{-1}. Water arsenic levels were low at 0.01 mg L^{-1}, but lead (Pb) and cadmium (Cd) were detected at higher concentrations. The results highlight regional variations in contamination levels across Ghana (Table 2).

3.4 Chronological records of heavy metal contamination in crops and food in Ghana

This section presents key findings from 2005–2024 on significant heavy metal contamination in Ghana's food systems.

In leafy vegetables, such as *Amaranthus spinosus* and *Corchorus olitorius*, iron levels (36.18 mg kg^{-1} and 27.59 mg kg^{-1}) exceeded safe limits. Lettuce irrigated with wastewater in Accra contained high levels of cadmium (1.1 mg kg^{-1}), chromium (1.1 mg kg^{-1}), and lead (10.2 mg kg^{-1}).[42] In cereals, arsenic levels in rice and legumes at Tamale's Aboabo Market exceeded permissible limits, while lead in maize and millet from Tolon District also surpassed safety thresholds.[43,44] Fish from Korle Lagoon and Tema Newtown markets showed unsafe levels of zinc (12 370.88 μg kg^{-1}), copper (773.65 μg kg^{-1}), and mercury (156.39 μg kg^{-1}).[45] Cocoa beans from Kukurantumi had elevated levels of copper (48.67 mg kg^{-1}) and cadmium (0.203 mg kg^{-1}), reflecting environmental impacts on cultivation.[46] Contamination of lettuce and spring onions near KNUST with arsenic, cadmium, chromium, and mercury exceeded recommended limits, as did mercury levels in lettuce and peppers from Haatso, Dzorwulu, and WISS irrigation sites.[47,48] In the Gulf of Guinea, silverfish gills and sediments contained high lead and cadmium.[47] These findings are summarized in Table 8 for further reference.

3.4.1 Meta-analysis of heavy metal contamination in crops and fish. A meta-analysis was conducted based on eight selected studies (Table 8) that examined heavy metal contamination in crops and fish. The data were harmonized, and grouped medians (GMVs) were calculated using SPSS. Due to small sample sizes, standard errors were omitted, and data below threshold limits were excluded. Missing or undetected values are marked as NA.

Specifically, the meta-analysis revealed significant contamination in cocoa, with GMVs of 48.67 mg kg^{-1} for copper (Cu), 70.03 mg kg^{-1} for lead (Pb), and 41.60 mg kg^{-1} for iron (Fe). Fish showed high lead (5.97 mg kg^{-1}) and iron (156.39 mg kg^{-1}) contamination. Lettuce exhibited moderate contamination with lead (2.98 mg kg^{-1}) and cadmium (5.18 mg kg^{-1}), while onion showed moderate levels of lead (2.28 mg kg^{-1}) and cadmium (4.84 mg kg^{-1}). Maize and millet had low lead contamination (2.22 mg kg^{-1} and 2.28 mg kg^{-1}), while groundnuts and cowpea showed minimal arsenic contamination (0.07 mg kg^{-1} and 0.08 mg kg^{-1}). *Amaranthus spinosus* and *Corchorus olitorius* posed potential risks with high iron contamination (36.18 mg kg^{-1} and 27.59 mg kg^{-1}), respectively. Pepper showed slight mercury contamination (0.28 mg kg^{-1}). Rice and sorghum had low arsenic levels, and soybean showed no significant contamination (Table 3).

3.5 Chronological records of airborne heavy metal and sulfur in Ghana

Between 2005 and 2011, several studies documented the airborne deposition of heavy metals and sulfur in Ghana (Table 9). Aboh *et al.*[29] reported concentrations of manganese (Mn: 2.74 ng m^{-3}), zinc (Zn: 2.0 ng m^{-3}), and nickel (Ni: 15 ng m^{-3}) in PM2.5–10 at Kwabenya, Accra, with sulfur concentrations measured at 146.4 ng m^{-3}. Later, Aboh *et al.*[52] observed significantly higher values of manganese (Mn: 279 ng m^{-3}), zinc (Zn: 59.8 ng m^{-3}), and lead (Pb: 21.8 ng m^{-3}), with sulfur levels ranging from 319 to 1310 ng m^{-3} in PM2.5–10 during both Harmattan and non-Harmattan periods.

Arkua *et al.*[53] documented high levels of manganese (Mn: 30.5 ng m^{-3}), copper (Cu: 10 ng m^{-3}), zinc (Zn: 65.5 ng m^{-3}), and lead (Pb: 24.5 ng m^{-3}) in PM10 at James Town/Usher Town and Nima in Accra, alongside sulfur concentrations of 1412.6 ng m^{-3}. Zhou *et al.*[30] reported airborne chromium (Cr: 1–2 ng m^{-3}), nickel (Ni: 2–4 ng m^{-3}), copper (Cu: 2–6 ng m^{-3}), zinc (Zn: 15–45 ng m^{-3}), and lead (Pb: 4–31 ng m^{-3}) in Accra locations (Asylum Down, Nima and East Legon) from 2007 to 2008, with sulfur concentrations between 524 and 1310 ng m^{-3}. In 2011, Safo-Adu *et al.*[54] found arsenic (As: 0.059 μg m^{-3}), chromium (Cr: 0.115 μg m^{-3}), nickel (Ni: 0.218 μg m^{-3}), lead (Pb: 0.011 μg m^{-3}), and cadmium (Cd: 0.007 μg m^{-3}) along the Accra-Tema highway.

Table 3 Heavy metal (arsenic (As), copper (Cu), lead (Pb), zinc (Zn), cadmium (Cd), manganese (Mn), chromium (Cr), iron (Fe), and mercury (Hg)) contamination in crops and fish: grouped median values and interpretation of risks

	Crops	As (mg kg^{-1})	Cu (mg kg^{-1})	Pb (mg kg^{-1})	Zn (mg kg^{-1})	Cd (mg kg^{-1})	Mn (mg kg^{-1})	Cr (mg kg^{-1})	Fe (mg kg^{-1})	Hg (mg kg^{-1})	Remarks[a]
Leafy vegetable	*Amaranthus spinosus*	NA[b]	NA	NA	NA	NA	NA	NA	36.18	NA	Fe slightly elevated
	Corchorus olitorius	NA	NA	NA	NA	NA	NA	NA	27.59	NA	Moderate Fe levels
	Lettuce	2.38	6.30	2.98	10.60	5.18	NA	14.50	NA	5.87	Elevated As, Pb, Cd, Cr, and Hg
ML[c]		0.1	73.3	0.3	99.4	0.1	—	2.3	425.5	0.03	Source[49,51]
Cereals	Maize	0.05	NA	2.22	NA	NA	NA	NA	NA	NA	High Pb contamination
	Millet	0.06	NA	2.28	NA	NA	NA	NA	NA	NA	High Pb and low As
	Rice	0.15	NA	NA	NA	NA	NA	NA	NA	NA	As within the acceptable range
	Sorghum	0.07	NA	NA	NA	NA	NA	NA	NA	NA	Minimal As contamination
ML		0.015	73	0.2	99.4	0.1–0.2	—	2.3	—	5.87	Source[50]
Legumes	Cowpea	0.08	NA	NA	NA	NA	NA	NA	NA	NA	Low As contamination
	Groundnuts	0.07	NA	NA	NA	NA	NA	NA	NA	NA	Minimal As contamination
	Soybean	0.06	NA	NA	NA	NA	NA	NA	NA	NA	As slightly elevated
ML					0.1	0.1[a]					Source[49,51]
Fruiting vegetable	Cocoa	NA	48.67	NA	70.03	0.20	NA	NA	41.60	NA	Fe near ML, moderate
	Pepper	NA	NA	NA	NA	NA	NA	NA	NA	0.28	Slightly elevated Hg
ML		—	—	—	0.05	0.05–0.3		—	—	—	Source[49,51]
Bulb vegetable	Onion	1.81	NA	2.39	NA	4.84	NA	8.93	NA	5.23	Multiple elevated metals
ML		—	—	0.6[a]	0.1	0.05	—	—	—	—	Source[49,51]
Animal products	Fish	NA	0.77	5.97	12.37	14.11	12.82	NA	NA	156.4	High Cd, Pb, Mn, and Hg
ML		—	—	0.5	0.3	0.2	—	—	—	1.0	Source[49,51]

[a] Remarks: remarks are based on comparisons with established critical limits from multiple sources to highlight general trends. [b] NA: not available or not detected. [c] ML = maximum level of heavy metal.

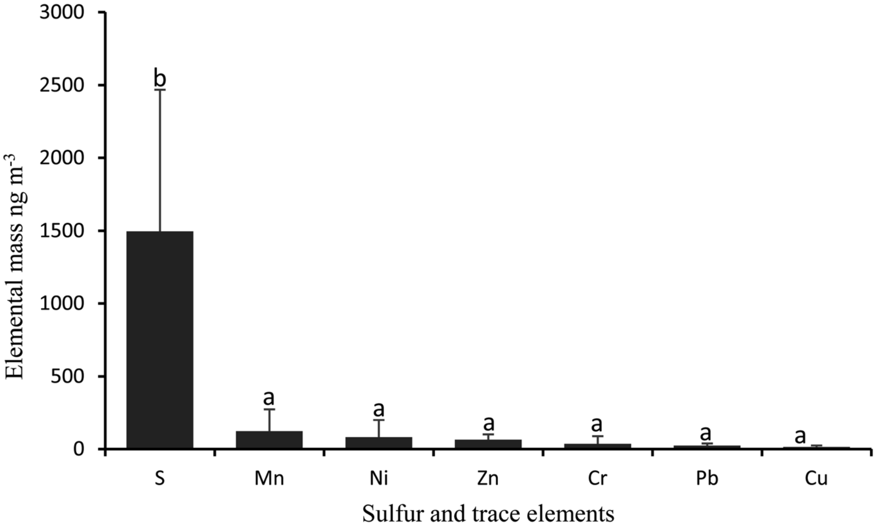

Fig. 4 Elemental mass levels and trends of sulfur (S) and heavy metals manganese (Mn), nickel (Ni), zinc (Zn), chromium (Cr), lead (Pb), and copper (Cu) in particulate matter across southern Ghana.

3.5.1 Meta-analysis of airborne heavy metal and sulfur across Ghana. A meta-analysis was conducted on airborne heavy metals and sulfur data from five selected studies (Table 9). Measurements from PM2.5, PM10, and PM2.5–10 fractions were standardized, and mean concentrations were computed using univariate analysis of variance (ANOVA) using SPSS software.

The results indicate that sulfur constituted the largest proportion of pollutants at 81.4% followed by manganese (6.7%), nickel (4.5%), and zinc (3.5%). Fig. 4 presents the relative abundance of each contaminant. The data reflect higher concentrations of airborne pollutants in southern Ghana, while comparable data for other regions remain limited.

3.6 Chronological record of reactive nitrogen, sulfate, and heavy metal concentrations in rainwater in Ghana

Between 1997 and 2014, several studies documented the concentration of reactive nitrogen, sulfur, and heavy metals in rainwater across Ghana (Table 10). In Tamale (1997–1998), sulfate (SO_4^{2-}) concentrations ranged from 0.43 to 6.7 mg L^{-1}, exceeding nitrate (NO_3^-) levels, which were consistently below 0.3 mg L^{-1}. pH levels during this period indicated slightly acidic to neutral conditions. Similar trends were observed in 2013, with sulfate ranging from 0.04 to 8.2 mg L^{-1} and nitrate concentrations below 6.5 mg L^{-1}.[55,56]

In Ayanfuri (2014), rainwater samples showed lead concentrations between 0.14 and 0.36 mg L^{-1} and cadmium between 0.30 and 0.38 mg L^{-1}, both exceeding WHO permissible limits. Sulfate levels ranged from 11.53 to 18.36 mg L^{-1}, while nitrate concentrations varied from 0.46 to 2.23 mg L^{-1}.[57] In Obuasi (2007), recorded lead levels ranged from 0.15 to 0.19 mg L^{-1}, and rainwater pH levels ranged between 4.0 and 5.6, indicating acidity.[58] Across regions, sulfate was the dominant anion, with elevated heavy metal concentrations more frequently observed in mining zones.

3.6.1 Meta-analysis of reactive nitrogen, sulphate, and heavy metals in rainwater. A meta-analysis of rainwater quality in Ghana between 1997 and 2014 was conducted using data from studies summarized in Table 10. The analysis focused on pH values and concentrations of ammonium (NH_4^+), nitrate (NO_3^-), sulfate (SO_4^{2-}), and selected heavy metals such as Pb, Zn, Cd, Fe, and Mn. Data were categorized by region—Northern, Southern, and Central Ghana, and regional averages were calculated to minimize the effect of outliers (Table 4).

Sulfate was identified as the dominant pollutant, potentially linked to industrial activities and mining with the highest contamination in the Central region (50.30%), followed by the Southern (36.94%) and Northern (12.77%) regions. Nitrate concentrations were highest in the Northern region (53.28%) and lowest in the Southern region (9.54%). pH measurements

Table 4 Chemical composition of rainwater (pH), ammonium (NH_4^+), nitrate (NO_3^-), sulphate (SO_4^{2-}), lead (Pb), zinc (Zn), cadmium (Cd), iron (Fe), and manganese (Mn) across Ghana's regions (1997–2014)[a]

Geography of locations	pH	NH_4^+ (mg L^{-1})	NO_3^- (mg L^{-1})	SO_4^{2-} (mg L^{-1})	Pb (mg L^{-1})	Zn (mg L^{-1})	Cd (mg L^{-1})	Fe (mg L^{-1})	Mn (mg L^{-1})
Northern region	7.18	NA	1.49	3.84	NA	NA	NA	NA	NA
Southern region	4.68	0.08	0.27	11.10	0.17	0.10	NA	0.11	NA
Central region	6.62	NA	1.04	15.11	0.27	NA	0.12	0.51	0.28

[a] NA: not available; data for these parameters were not reported in the referenced studies.

indicated the prevalence of acidic rain (pH < 6.5) in the Southern and Central regions, while the Northern region exhibited pH values within safe limits. Although heavy metal data were limited, elevated levels of lead were noted in mining areas such as Obuasi and Ayanfuri, surpassing recommended safety thresholds.

4. Human and environmental impacts

The widespread contamination of environmental media in Ghana by heavy metals, sulfur, and reactive nitrogen compounds presents escalating risks to human health and ecosystems. These pollutants circulate through dust, soil, water, and air, with their deposition and bioaccumulation compounding adverse effects over time. Major sources include atmospheric deposition, agricultural runoff, mining, and industrial emissions.

Airborne dust rich in metals such as manganese, zinc, and nickel substantially deteriorates air quality, particularly in urban and mining zones. This increases respiratory and cardiovascular diseases. These particles also deposit onto soils and water bodies, triggering secondary contamination with persistent health consequences.[38,39,51] The accumulation of toxic metals such as lead, arsenic, and cadmium disrupts soil fertility and plant productivity. This degradation worsens food

Table 5 Chronological record of dust deposition in Ghana

Year	Study/ source	Location	Type of deposition	Season of measurement	Non-point sources	Key findings
1993	59	Sahelian and Gulf of Guinea	Flux deposition	June to October	N/A	The Sahelian zone shows the highest dust deposition (1300 kg per ha per year), while the more humid Guinean zone has lower levels (365 kg per ha per year)
2001–2002	2	Bawku, Tamale and Sefwi Bekwai	Dust deposition	November–March	Harmattan dust events	Dust deposition ranged from 25 g m^{-2} in Bawku to 16 g m^{-2} in Tamale and 5 g m^{-2} in Sefwi Bekwai
2000–2003	60	Northern and southern	Dust deposition	Harmattan	Harmattan dust events	Average deposition per Harmattan season was 42 g m^{-2} in Bawku, 28 g m^{-2} in Tamale, and 12 g m^{-2} in the south
2002–2005	61	Gulf of Guinea between latitudes 5° and 12°N during the winter	Flux deposition	28 Jan.–3 Feb. (Julian day 28–34) in 2002 and 7 Jan.–15 Jan. (Julian day 7–15) in 2005	January to February dust events	Deposition rates were 13 t km^{-2} in 2002 and 31 t km^{-2} in 2005 during peak Harmattan dust events
2000–2005	62	Northern and southern Ghana	Dust deposition	N/A	Harmattan dust events	Northern Ghana (Bawku) received more dust (37.0 g/0.23 m^2 per year) than southern Ghana (Kpong: 14.4 g/0.23 m^2 per year)
2002–2006	3	Northern, Central, and Southern Ghana	Dust deposition	N/A	Harmattan dust events	Deposition declined from 160 kg ha^{-1} in Northern Ghana to 60 kg ha^{-1} in Southern Ghana
2002–2007	63	Tamale, Kete Krachi, and Kpong	Dust deposition	N/A	Harmattan dust events	Average deposition ranged from 19.5 t km^{-2} in Tamale to 10 t km^{-2} in Kpong during the Harmattan season
2006–2009	25	Southern Ghana (Kade)	Dust deposition	N/A	Harmattan dust events	Average deposition over three Harmattan seasons was 13.53 g m^{-2}
2001–2013	26	Bolgatanga, Ghana	Aerosol loading and retention[a]	Aerosol loading and retention	Aerosol loading and retention	Atmospheric aerosol retention peaked at 64.27 mg m^{-2} in 2012
2022	28	Konongo, Ghana	Aerosol dust	November to December	Aerosol dust	Monthly average deposition near the factory was 60.2 g m^{-2}

[a] Although Emetere *et al.* did not specifically analyze dust deposition during the Harmattan season, the study examined aerosol retention influenced by atmospheric conditions typical of this period.

Table 6 Chronological records of particulate matter deposition in Ghana

Year	Study/ source	Location	Type of deposition	Season of measurements	Non-point sources	Key findings
1997–2005	17	Central Ghana	PM 2.5, PM5, and PM10	January–February	Sharan dust 56–97%	Found that the average aeolian dust contributions from Saharan PM2, PM5, and PM10 were approximately 599, 598, and 1037 μg m^{-3}, respectively, to the average Total Suspended Particles (TSP) of 1069 μg m^{-3} from 1997 to 2005 in the central Ghana region
2005–2006	18	Kwabena, Accra	PM 2.5 and PM10	December 2005 to February 2006	Transported PM2.5 – PM10	Found that average fine particles: 8.57 μg m^3; average coarse particles: 110.9 μg m^{-3} (exceeds WHO and Ghana EPA guidelines of 70.0 μg m^{-3} for 24-hour average and 50.0 μg m^{-3} yearly average). Fine particles are below WHO guidelines
2006–2007	29	Kwabena, Accra, Ghana	PM2.5 and PM10	February 2006 to February 2007	Local and transported PM2.5–10	Found that for PM (2.5–10), the average mass concentration during Harmattan is 389 μg m^{-3} and 54.0 μg m^{-3} during non-Harmattan. For PM2.5, the average mass concentration is 96.5 μg m^{-3} during Harmattan and 22.9 μg m^{-3} during non-Harmattan
2005–2007	52	Kwabenya, Accra, Ghana	PM2.5 and PM10	28th Dec. 2005–31 Mar. 2006, 4th Apr. – 31 Oct. 2006, and 2nd Nov. 2006 – 15th Feb. 2007	Local and transported PM2.5–10	Found that coarse mass concentration peaks are at 473.37 μg m^{-2} during the 2006/07 Harmattan, significantly higher than 42.81 μg m^{-2} in the rainy season. Fine mass concentration was lowest in the 2005/06 Harmattan season (10.59 μg m^{-2}) and highest in 2006/07 (85.91 μg m^{-2}), with a maximum of 430.23 μg m^{-2}, highlighting seasonal fluctuations
2007–2008	30	James Town/Usher Town (JT), Asylum down (AD), Nima (NM) and East Legon (EL)	PM2.5 and PM10	September 2007 to August 2008	September 2007 to August 2008	During Harmattan, crustal particles accounted for 55 μg m^{-3} (37%) of fine particle (PM25) mass and 128 μg m^{-3} (42%) of (PM10) mass. Outside Harmattan, biomass combustion, which was associated with higher black carbon, potassium, and sulfur, accounted for between 10.6 and 21.3 μg m^{-3} of fine particle mass in different neighborhoods
2008	64	Ashaiman, Accra	PM2.5 and PM10	February to August	Transported PM2.5–10	The mean mass concentration levels for the coarse and fine particulates obtained within the period of investigation were 89.2 μg m^{-3} and 21.6 μg m^{-3} respectively
2008	65	Tarkwa Township, Ghana	PM > 10	February to June	PM > 10 μm	The minimum and maximum concentrations were 1.3 and 110 μg m^{-3}, respectively, with an average of 27 μg m^{-3}
2006–2008	66	Accra, Ghana	PM2.5 and PM10	April 2007 (before the main rainy season) in AD and in July–	April 2007 (before the main rainy season) in AD	Found that PM2.5 concentrations reached 200 μg m^{-3} and PM10 reached 400 μg m^{-3} in neighborhoods, with medians of 53.4 μg m^{-3} for

Table 6 (*Contd.*)

Year	Study/ source	Location	Type of deposition	Season of measurements	Non-point sources	Key findings
				August 2007 (after the main rainy season)	and in July–August 2007 (after the main rainy season)	PM2.5 and 144.5 μg m^{-3} for PM10 along divided multi-lane highways
1997–2011	67	Kumasi, Ghana	PM2.5 and PM10	January to February	January to February	During the Harmattan period from 1996 to 2000, the average dust concentration was measured at 370 μg m^{-3}. In the following period, from 2001 to 2011, this average increased significantly to 1262 μg m^{-3}, indicating a notable increase in airborne dust levels over time
2011	54	Tema, Accra	Ambient air particulates	November to December	November to December	Found that the average PM10 concentration along the Accra-Tema highway was 86.97 μg m^{-3}, exceeding the WHO guideline of 50 μg m^{-3}. PM10 levels varied significantly throughout the week, primarily due to changes in vehicular density
2015–2019	31	Tarkwa, Ghana (15 Communities)	PM10 and TSP	Dry/wet seasons	Dry/wet seasons	In wet/dry deposition, it has been found that TSP and PM10 concentrations were consistently higher in the dry season, with TSP peaking at 118.5 μg m^{-3} in 2017 and PM10 at 60.2 μg m^{-3}. Both pollutants increased from 2015 to 2018, with TSP reaching 99.1 μg m^{-3}, before declining slightly in 2019
2019–2020	19	GAMA, Accra	PM2.5	April to June 2019 to June 2020	Wet/dry seasons	Found that the overall annual mean PM2.5 is 37 μg m^{-3}, increasing to 89 μg m^{-3} during Harmattan. Community-based initiative sites show a similar trend, with Harmattan levels reaching 94 μg m^{-3}. High-density areas average 87 μg m^{-3}, while peri-urban sites have the lowest annual mean of 26 μg m^{-3}, increasing to 81 μg m^{-3} in Harmattan, indicating significant seasonal variation
2020–2021	32	Accra, Ghana (four urban sites)	PM2.5	February 2020 to June 2021	Wet/dry seasons	Annual average PM2.5 concentrations vary between 17 and 26 μg m^{-3}. PM2.5 differences between sites within a city, especially between traffic impacted and urban background sites, are larger than the differences between the two cities. These annual averages exceed World Health Organization (WHO) annual pollution thresholds from the 2005 (10 mg m^{-3}) and 2021 (5 mg m^{-3}) guidelines

Table 6 (*Contd.*)

Year	Study/ source	Location	Type of deposition	Season of measurements	Non-point sources	Key findings
2021	68	Tema, Accra, Ghana	PM2.5, PM10, and TSP	9 months	9 months	Found that average PM2.5: 38.094 μg m^{-3} (exceeds the safe limit). PM10: 56.243 μg m^{-3} (exceeds the IFC limit and is below the Ghana limit). TSP: 75.122 μg m^{-3} (below the Ghana limit)
2020–2022	33	Cantonments, Dzorwulu intersection, Roman Ridge, and Tetteh Quarshie Interchange	PM2.5	December to February	December to February	Found that during the Harmattan season, PM2.5 values in Cantonments can be alarmingly high. On January 21, 2022, the AQI reached 204 μg m^{-3}, while nearby areas recorded 169 μg m^{-3} (Dzorwulu intersection), 184 μg m^{-3} (Roman Ridge), and 183 μg m^{-3} (Tetteh Quarshie Interchange)

insecurity by impairing crop yields and contaminating food chains, especially in mining-affected regions where contamination is chronic and widespread.[5,11,28,34]

Elevated concentrations of heavy metals and nitrogen compounds in water sources pose direct risks to both human and aquatic health. Persistent exposure to metals such as lead and cadmium is associated with kidney damage, cancer, and other serious illnesses. Moreover, nitrogen-induced eutrophication threatens aquatic biodiversity by depleting oxygen levels.[13,16,21,38,48] Sulfur and nitrogen emissions worsen environmental acidification and degrade air quality. Acid rain from sulfur compounds damages soils and vegetation, while nitrogen oxides contribute to respiratory problems, particularly in densely populated areas.[19,26,29,30,32,33]

Finally, bioaccumulation of heavy metals such as lead, cadmium, and mercury in crops and fish poses a chronic health risk to Ghanaian communities. Contamination near mining and industrial sites threatens food safety and increases risks of developmental and neurological disorders, highlighting the urgent need for monitoring and mitigation.[6–8,11,43,44]

5. Discussion

In this discussion, we integrate the key narrative findings with the meta-analytic results to provide a comprehensive understanding of regional variations in dust deposition, particulate matter levels, airborne aerosol contents, rainfall, heavy metal contamination, and their implications for both the environment and food safety in Ghana. Our synthesis also highlights temporal trends, including seasonal variations and evolving contamination patterns, to inform effective policy responses.

Our meta-analysis reveals significant geographical disparities in dust deposition during the Harmattan season, with the Northern region consistently showing the highest deposition rates. It accounted for the largest share of total dust deposition, followed by the Southern region, while the Central region, which serves as a transition zone, contributed the least (Fig. 3). This pattern highlights the predominance of dust accumulation in the north, although statistical tests did not confirm significant regional differences. Furthermore, although data gaps persist, some studies suggest increasing dust deposition rates in recent decades, potentially linked to land-use changes and climate variability. These temporal shifts underscore the need for long-term monitoring. A critical gap in the literature persists due to insufficient stratified data across urban, peri-urban, and rural areas. Future research should address this gap by enhancing regional dust deposition monitoring and developing high-resolution data sets for better urban-rural comparisons.

The findings are consistent with previous site-specific studies conducted between 1993 and 2022, including those by Emetere *et al.*[26] and Awuah *et al.*,[28] which reported similar spatial and seasonal variability. However, they do not fully account for the disparities in dust sources (Table 5). For example, peaks in dust deposition were observed in both northern and southern Ghana, particularly near industrial zones. Our meta-analysis builds on these studies by quantitatively synthesizing regional and seasonal differences, revealing

Table 7 Chronological records of environmental media (soil and water) contamination across Ghana

Year	Study/Source	Location	Type of deposition	Season of measurements	Non-point sources	Key findings
2008	69	Densu River Basin, Ghana	Soil from five-meter depth	Wet season (June)	N/A	Found stable iron concentrations (23.84–143.70 g kg^{-1}) in Densu River Basin soils, with leaching of base cations (K and Ca) near the surface. pH ranged from 5.6 to 8.3, indicating moderate acidity to alkalinity, while minimal metal enrichment was noted due to human activities
2008–2009	70	Tema Motorway, Tetteh Quarshie interchange, John Teye-Pokuase highway, and Mallam Junction-Weija road	Road dust	October 2008 to March 2009	October 2008 to March 2009	Found that titanium (Ti) ranged from 2206.76 to 3489.70 mg kg^{-1}; vanadium (V) from 28.14 to 197.00 mg kg^{-1}; chromium (Cr) from 123.75 to 220.37 mg kg^{-1}; manganese (Mn) from 235.93 to 379.63 mg kg^{-1}; iron (Fe) from 19 782.00 to 36 630.34 mg kg^{-1}; nickel (Ni) from 6.46 to 15.88 mg kg^{-1}; copper (Cu) from 29.01 to 76.53 mg kg^{-1}; zinc (Zn) from 124.52 to 371.66 mg kg^{-1}; bromine (Br) from 0.58 to 7.07 mg kg^{-1}; zirconium (Zr) from 662.75 to 1003.95 mg kg^{-1}; and lead (Pb) from 33.64 to 117.45 mg kg^{-1}. Notably, lead and zinc concentrations exceeded their respective alert values of 50 mg kg^{-1} and 300 mg kg^{-1}, indicating significant pollution levels
2009	34	Industrial Cluster in Kumasi, Ghana	Soil	March to May	N/A	Found that arsenic (As) was highest in zone 4 (18.6 mg kg^{-1}) and lowest in Kwantwima (1.4 mg kg^{-1}). Lead (Pb) peaked in zone 12 (571.3 mg kg^{-1}), mercury (Hg) ranged from 3.3 to 10.4 mg kg^{-1}, cadmium (Cd) from 5.0 to 13.2 mg kg^{-1}, and chromium (Cr) reached 545.8 mg kg^{-1} in zone 12. Zinc (Zn) was highest in zone 4 (908.6 mg kg^{-1}), while copper (Cu) ranged from 19.0 to 334.6 mg kg^{-1}, indicating significant contamination in specific areas
2008 to 2009	71	Mallam Junction-Weija road, John Teye-Pokuase road, Tema Motorway and Tetteh Quarshie Interchange in Accra	Road dust	October 2008 to March 2009	N/A	Found that the highest mean concentrations of elements in road dust were observed for potassium (K) at 13 500 mg kg^{-1} (Tema Motorway), calcium (Ca) at 25 600 mg kg^{-1} (Tetteh Quarshie Interchange), and iron (Fe) at 52 500 mg kg^{-1} (TQ), with lead (Pb) peaking at 150 mg kg^{-1} (TQ)

Table 7 *(Contd.)*

Year	Study/Source	Location	Type of deposition	Season of measurements	Non-point sources	Key findings
2011	72	Asonomaso, Ashanti, Ghana	Quarry dust	August to November 2011	August to November 2011	Found that secondary quarry dust has higher levels of manganese (0.975 mg kg^{-1}), iron (2.625 mg kg^{-1}), and lead (0.195 mg kg^{-1}) than primary dust and control. Copper is elevated in both quarry dusts (1.250–0.975 mg kg^{-1}) compared to control (0.140 mg kg^{-1}). Arsenic, mercury, and zinc are higher in quarry dusts than control, with similar zinc levels (0.2000 mg kg^{-1}) across dust types
2012	73	Bolgatanga municipality, Accra	Road dust	Dry season	Dry season	Found significant levels of chromium (Cr: 5.36 mg kg^{-1}, zinc (Zn: 3.45 mg kg^{-1}, mercury (Hg: 0.1 mg kg^{-1}), and cobalt (Co: 2.41 mg kg^{-1}), suggesting anthropogenic sources. Cadmium (Cd: 0.12 mg kg^{-1}, $p = 0.05$) also warrants attention, though it remains low. Other metals such as manganese (Mn: 69.06 mg kg^{-1}) and iron (Fe: 191.45 mg kg^{-1}) show no significant variation and stay below alert thresholds, indicating minimal immediate risk
2012	74	Lower Pra Basin of Ghana	Groundwater	January to April and June to October 2012	January to April and June to October 2012	Found that during dry season pH 6.06, high Pb (26.5 μg L^{-1}), Cd (2.40 μg L^{-1}), and Hg (3.30 μg L^{-1}) levels, all exceeding WHO limits, with elevated Fe, Mn, and Al concentrations. During the wet season, water had a low pH of 5.5, with high levels of Pb (34.5 μg L^{-1}), Cd (6.69 μg L^{-1}), Mn (203 μg L^{-1}), and Fe (298 μg L^{-1}), all exceeding WHO guidelines, while As and Hg remained within safe limits
2014 to 2015	75	Southwest Coast of Ghana in the wet and dry seasons	Drinking water samples	October 2014 to March 2015	October 2014 to March 2015	Found that arsenic concentrations in water samples during both wet (mean: 3.33 μg L^{-1}) and dry (mean: 3.21 μg L^{-1}) seasons were below the WHO limit of 10 μg L^{-1}. Lead levels exceeded the permissible limit, with means of 47.67 μg L^{-1} in the wet season and 70.73 μg L^{-1} in the dry season. Copper, selenium, zinc, and mercury concentrations were well below WHO standards
2015 to 2016	76	Tamale Metropolis	Groundwater	December 2015 to March 2016	December 2015 to March 2016	Found that groundwater in the Tamale Metropolis showed ammonia levels

Table 7 (*Contd.*)

Year	Study/Source	Location	Type of deposition	Season of measurements	Non-point sources	Key findings
						(0.46 mg L^{-1}) below WHO limits (1.5 mg L^{-1}), while calcium (50.75 mg L^{-1}) and chloride (94.21 mg L^{-1}) were safe. However, cadmium (0.02 mg L^{-1}), lead (0.02 mg L^{-1}), and total iron (0.34 mg L^{-1}) exceeded WHO limits, and turbidity averaged 22.03 NTU, surpassing the recommended 5 NTU
2016	77	Nandom District in semi-arid Northwestern Ghana	Soils in cultivated fields (or farms) and water samples from rivers, boreholes, and dug-out wells	March to August	March to August	Found that soils in the Nandom district had elevated heavy metal levels: chromium (0.456 mg kg^{-1}), iron (214.8 mg kg^{-1}), lead (0.854 mg kg^{-1}), nickel (2.813 mg kg^{-1}), and arsenic (1.753 mg kg^{-1}), exceeding WHO and FAO limits. Water sources were safe for irrigation but had high levels of total suspended solids, turbidity, and coliforms, necessitating treatment to ensure public health safety
2015–2017	20	Ashaiman and Tema urban areas, Ghana	Soil	Local soil	N/A	Found elevated copper (Cu), nickel (Ni), zinc (Zn), and lead (Pb) levels at e-waste sites, with Pb reaching 393.04 mg kg^{-1} in ASH topsoil. Cu levels are high in subsoil at GMG (551.90 mg kg^{-1}) and ASH (442.40 mg kg^{-1}). Mercury (Hg) and cadmium (Cd) exceed optimum values but are below action levels, indicating significant contamination from e-waste activities
2017	78	Kumasi, Ghana	Urban soil	N/A	N/A	Found that the study in Kumasi, Ghana, assessed the risk of incidental ingestion of metal contaminants in surface soils from commercial areas, revealing that arsenic, chromium, copper, lead, and zinc exceeded international soil quality guidelines in some samples
2016 to 2017	79	Northern and Upper East regions of Ghana	Groundwater	October 2016 to March 2017	October 2016 to March 2017	Found that groundwater quality assessments in Northern Ghana ($n = 112$) and the Upper East Region ($n = 116$) revealed mean temperatures of 29.7–29.8 °C. Northern Ghana had acceptable conductivity (513.53 μS cm^{-1}) and TDS (93.10 mg L^{-1}), but elevated nitrate (14.39 mg L^{-1}) and iron levels

Table 7 (*Contd.*)

Year	Study/Source	Location	Type of deposition	Season of measurements	Non-point sources	Key findings
						($1.974\ \mathrm{mg\ L^{-1}}$) that raised concerns. The Upper East region showed lower conductivity ($257.0\ \mathrm{\mu S\ cm^{-1}}$) and TDS ($43.7\ \mathrm{mg\ L^{-1}}$) with similar nitrate ($16.315\ \mathrm{mg\ L^{-1}}$) and iron ($0.986\ \mathrm{mg\ L^{-1}}$) issues. While lead and arsenic were within limits, variability in other parameters indicates potential water quality concerns
2019	35	Kpone Landfill site Ghana	Soil surface to a depth of 30 cm	February	February	Found that zone E showed the highest contamination, with elevated levels of lead ($351.67\ \mathrm{mg\ kg^{-1}}$), zinc ($1875.67\ \mathrm{mg\ kg^{-1}}$), and copper ($79.87\ \mathrm{mg\ kg^{-1}}$), compared to other zones, highlighting significant pollution in this area
2019	80	Small-scale mining communities in the Amansie West District of Ashanti Region, Ghana	Topsoil (0–20 cm)	November	November	Found similar arsenic levels across mined sites ($5.46\ \mathrm{mg\ kg^{-1}}$), farmland ($5.59\ \mathrm{mg\ kg^{-1}}$), and forest areas ($5.67\ \mathrm{mg\ kg^{-1}}$), but lead was significantly higher in mined sites ($10.45\ \mathrm{mg\ kg^{-1}}$) than in farmland ($1.26\ \mathrm{mg\ kg^{-1}}$) and forest ($1.08\ \mathrm{mg\ kg^{-1}}$). Mercury levels exceeded FAO/WHO limits (0.68 to $17.03\ \mathrm{mg\ kg^{-1}}$), highlighting significant contamination differences by land use and the need for effective remediation strategies
2020	21	Kumasi peri-urban area, Ghana	Ground water	N/A	N/A	Found that hand-dug wells (HDWs) in Kumasi have higher contamination levels compared to mechanized boreholes (MBHs). For HDWs, pH levels (mean 6.54) are slightly above the WHO guideline (6.5–8.5) and lead (Pb) concentrations (mean $0.022\ \mathrm{mg\ L^{-1}}$) exceed the WHO limit of $0.01\ \mathrm{mg\ L^{-1}}$. Electrical conductivity (EC) is high in HDWs ($371.39\ \mathrm{\mu S\ cm^{-1}}$), along with total dissolved solids (TDS) at $204.45\ \mathrm{mg\ L^{-1}}$. Nitrate ($NO_3$) levels in HDWs (mean $26.53\ \mathrm{mg\ L^{-1}}$) exceed the WHO limit of $50\ \mathrm{mg\ L^{-1}}$. In contrast, MBHs show lower contamination with values within the WHO guidelines for most parameters tested
2020	81	Arterial roads (Kumasi-Accra, Kumasi-Offinso	Ambient air	N/A	N/A	Found that significant differences in pollutant concentrations were found

Table 7 (*Contd.*)

Year	Study/Source	Location	Type of deposition	Season of measurements	Non-point sources	Key findings
		and Kumasi-Mampong roads) in the Kumasi Metropolis, Ghana				among arterial roads for carbon monoxide (CO: $F(3, 8) = 14.396, p < 0.001$) and sulfur dioxide ($SO_2$: $F(3, 8) = 17.726$, $p < 0.001$). In contrast, nitrogen dioxide (NO_2: $F(3, 8) = 2.978$, $p = 0.097$) and volatile organic compounds (VOCs: $F(3, 8) = 1.275$, $p = 0.347$) showed no significant differences
2020–2021	82	Pra and Ankobra in the Southwestern region of Ghana	Estuary water	July 2020 to July 2021	July 2020 to July 2021	Found that in the Pra and Ankobra estuaries, pH levels were acceptable (Pra: 7.24; Ankobra: 6.85), but dissolved oxygen (DO) was low (Pra: 4.49 mg L^{-1}; Ankobra: 4.31 mg L^{-1}). Nitrate–nitrogen (NO_3–N) concentrations were below the USEPA guideline (Pra: 1.28 mg L^{-1}; Ankobra: 1.48 mg L^{-1}). Arsenic (As) exceeded guidelines (Pra: 26.50 μg L^{-1}; Ankobra: 20.70 μg L^{-1}), and cadmium (Cd) was higher in Ankobra (0.50 μg L^{-1}) than in Pra (0.12 μg L^{-1}). Overall, heavy metal pollution and low oxygen levels ($N = 30$) are concerning for both estuaries
2021	38	Pra River Basin, Ghana	Surface water	May and June 2019	N/A	Found that the Pra River Basin shows heavy metal contamination, with lead (Pb) averaging 18.73 μg L^{-1} in the Offin sub-basin, exceeding the WHO limit of 10 μg L^{-1}. Total nitrogen averages 2.88 mg L^{-1}, below the WHO limit of 10 mg L^{-1}, indicating acceptable nitrogen levels but significant risks from lead pollution
2021	83	Haatso-Atomic Road, Accra	Bioaccumulation	Tree rings	Tree rings	Found that tree rings from *Swietenia mahagoni* (1957–2018) indicated heavy metal pollution along the Haatso-Atomic road. Metal concentrations (mg kg^{-1}) exceeded WHO guidelines: Cu (3.15–9.84), Mn (2.58–5.49), Zn (8.18–15.78), Pb (0.12–0.60), Cd (0.01–0.09), and Ni (0.10–0.99). Growth rates were higher during wet seasons
2021	36	Tema Industrial Area, Accra	Bioaccumulation	Tree rings	Tree rings	Found that tree rings from *Swietenia mahagoni* (1968–2018) revealed heavy metal pollution in the Tema industrial area. Concentrations (mg kg^{-1}) were Cu (1.92–6.70), Zn (5.37–13.9), Fe (0.10–

Table 7 (*Contd.*)

Year	Study/Source	Location	Type of deposition	Season of measurements	Non-point sources	Key findings
						0.36), and Pb (12.13–90.13), with Cu and Zn exceeding WHO guidelines
2021–2022	84	UMaT, Bra Habobom, A'koon, Boboobo and Bogoso Junction (areas in Tarkwa, a mining town in Ghana)	Top soil	N/A	N/A	Found that heavy metal concentrations in urban topsoil exceeded WHO/FAO guidelines, with notable levels: Cd (0.164 mg kg^{-1}), Co (8.153 mg kg^{-1}), Cr (47.343 mg kg^{-1}), Cu (33.387 mg kg^{-1}), Pb (57.912 mg kg^{-1}), Zn (70.063 mg kg^{-1}), and Mn (5206.416 mg kg^{-1}). Urgent remediation is needed to address health risks from this contamination
2022	37	Haatso-Atomic Road Area, Accra	Soil	N/A	N/A	Found that at Haatso-Atomic Road in the Greater Accra region, aluminum (Al) has the highest crustal average at 82 300 ppm, followed by silicon (Si) at 281 500 ppm and iron (Fe) at 56 300 ppm. Sodium (Na) averages 23 600 ppm, and calcium (Ca) averages 41 500 ppm, while trace elements such as lead (Pb) and copper (Cu) are present at lower concentrations of 12.5 ppm and 55 ppm, respectively. These data establish a baseline for assessing potential pollution levels and heavy metal enrichment in the area
2023	85	Tamale	Soil of a high traffic transport station and a low traffic transport station	N/A	N/A	Found that iron (Fe) is the most concentrated heavy metal in soil, with 2460 mg kg^{-1} in high traffic transport stations and 2390 mg kg^{-1} in low traffic stations. Manganese (Mn) follows at 581.6 mg kg^{-1} and 423.2 mg kg^{-1}, while zinc (Zn) is 165.7 mg kg^{-1} and 254.4 mg kg^{-1}, respectively. Lead (Pb) and nickel (Ni) have mean concentrations of 17.2 mg kg^{-1} and 15 mg kg^{-1}, respectively, with cadmium (Cd) at 24.9 mg kg^{-1}. Limits of detection (LOD) are low for all metals
2023	39	A mining Community (Kenyasi) and a non-mining community (Sunyani) in Ghana	Surface soil (0–10 cm)	N/A	N/A	Found that mining communities show higher average levels of As (7.31 mg kg^{-1}), Cd (17.32 mg kg^{-1}), Cu (33.09 mg kg^{-1}), and Zn (159.19 mg kg^{-1}), with significant differences compared to non-mining areas, especially for As, Cd, and Zn ($p < 0.05$)

Table 7 (*Contd.*)

Year	Study/Source	Location	Type of deposition	Season of measurements	Non-point sources	Key findings
2023	86	Sokoban wood village, Ghana	Boreholes and hand-dug wells	N/A	N/A	Found that several parameters exceeded WHO limits: pH below 6.5 in HW 01, HW 03, HW 05, HW 12, BH 14, and BH 16; conductivity above 400 µS cm^{-1} in HW 12; TDS over 500 mg L^{-1} in HW 12; nitrate higher than 50 mg L^{-1} in HW 12; lead above 0.01 mg L^{-1} in HW 05; and iron exceeding 0.3 mg L^{-1} in HW 01, BH 14, BH 16, and BH 19
2011–2023	87	Nationwide	Soil, air, and water	N/A	N/A	Found that heavy metals, PBDEs, and PAHs pose significant risks to public health and food safety. Urgent environmental management is needed
2024	88	Obuasi municipality, Ghana	Soil	Soil	N/A	Found that arsenic (As) averaged 175.14 mg kg^{-1}, exceeding guidelines; cadmium (Cd) was 6.30 mg kg^{-1}; chromium (Cr) averaged 75.45 mg kg^{-1}; lead (Pb) reached 24.22 mg kg^{-1}; and copper (Cu) was 36.22 mg kg^{-1}. Manganese (Mn) averaged 228.19 mg kg^{-1}, nickel (Ni) was 33.05 mg kg^{-1}, and zinc (Zn) averaged 124.06 mg kg^{-1}. The soil pH was 7.05, indicating significant contamination risks from metal exposure in the area

a complex interplay of natural and anthropogenic factors that is not always captured in single-site studies. This highlights the necessity of integrated regional assessments.

Northern Ghana's proximity to the Sahara Desert makes it more susceptible to Harmattan dust transport, particularly from November to March. As these winds move southward, their intensity diminishes, leading to lower dust accumulation in the southern regions.[2,3] Additionally, localized emissions from industrial activities, especially in the south, further shape regional dust patterns. Topographical differences also influence deposition rates: higher elevations in the north promote dust settling, while lower altitudes in the south facilitate greater dispersion. Rainfall variability plays a significant role in these differences; southern Ghana, with higher precipitation levels, experiences more efficient airborne dust washout, whereas the drier north undergoes longer periods of dust accumulation.[26,28] Moreover, recent studies suggest intensification of dust storms in northern Ghana, potentially linked to deforestation and land-use changes, amplifying health risks in already vulnerable regions. These combined factors highlight the complex interaction between regional, seasonal, and local influences on dust deposition patterns. This complexity calls for a more integrated approach to studying environmental pollution, one that accounts for both large-scale atmospheric factors (*e.g.*, Harmattan winds) and localized human activities (*e.g.*, industrial emissions).

Our meta-analysis of particulate matter (PM) deposition in Ghana reveals significant regional disparities, especially in seasonal variations. Unlike dust deposition patterns, PM levels were highest in the Central region, which recorded Grouped Median Concentrations (GMCs) of 489.00 μg m^{-3} for PM2.5, 703.50 μg m^{-3} for PM10, and 710.50 μg m^{-3} for Total Suspended Particles (TSP). In contrast, the Southern and Southwest regions had lower PM deposition, especially outside the Harmattan period. The Southern region's GMCs for PM2.5 (89.00 μg m^{-3}), PM10 (119.45 μg m^{-3}), and TSP (370.00 μg m^{-3}) were notably lower than those in the northern and central regions. Notably, PM concentrations have shown an increasing trend since 2000, linked to urbanization, vehicular traffic, and industrial growth, exacerbating air quality concerns.

The findings support previous individual studies, emphasizing the impact of local environmental conditions on PM deposition trends. Between 1997 and 2022, PM concentrations surged during the Harmattan season (Table 6), primarily due to Saharan dust intrusions. Several studies[17,18,29,30] reported PM peaks frequently exceeding WHO safety limits. More recent studies,[19,31] along with measurements by Bahino *et al.*[32] and Gyasi *et al.*,[33] confirm persistently high PM levels, particularly in Accra. These persistently high PM levels pose severe public health challenges, including increased respiratory diseases and economic losses due to reduced productivity.

The observed seasonal and regional PM variations can be attributed to Saharan dust transport, influenced by Ghana's proximity to the Sahara and prevailing northeast trade winds. Urban contributions, such as vehicle emissions, industrial activities, and construction, exacerbate natural dust sources. Limited rainfall during the Harmattan season reduces airborne particle washout. These factors, coupled with climate change-driven dust storms, likely contribute to the currently elevated PM levels during this period.[17–19,29–33] This convergence of natural and anthropogenic drivers highlights cumulative exposure risks that disproportionately affect vulnerable populations in urban and mining areas. Given the growing concern about air pollution, this underscores the urgent need for implementing long-term monitoring systems to better understand the seasonal and regional impacts of airborne pollutants on human health.

Our meta-analysis of environmental media contamination (soil and water) across Ghana revealed distinct regional variations in heavy metal levels (Table 7). Notably, data for the Central region were unavailable, limiting direct comparisons. The Northern region exhibited moderate concentrations of lead (Pb) and cadmium (Cd) in water (0.02 mg L^{-1}) along with nitrate (NO_3^-) levels in soil (15.35 mg L^{-1}). In contrast, the Southern region showed higher contamination, particularly in arsenic (As), copper (Cu), and zinc (Zn) levels. In the Southwestern region, manganese (Mn) concentrations were significantly elevated (5206.42 mg kg^{-1}), and lead and cadmium levels in water were also concerning (Table 2). Our analysis indicates that contamination levels have increased in urban areas due to rapid industrialization, underscoring the need for stricter regulation and pollution control measures.

The results support prior studies incorporated into our meta-analysis, which identified high levels of reactive nitrogen, sulfur, and heavy metals in urban and peri-urban areas, particularly in Kumasi, Accra, and the Kpone landfill site. Accra, for example, has been reported to have concerning levels of aluminum, silicon, and iron in soil, as documented by Edusei *et al.*[36,37] Mining hubs such as Obuasi and Kenyasi continue to exhibit persistent arsenic and cadmium contamination, attributed to intensive mining practices. Several key factors contribute to regional variation in contamination, including industrial and vehicular emissions in urban areas such as Accra and Kumasi, significantly elevating lead, arsenic, and cadmium concentrations. Mining activities in Obuasi and Kenyasi contribute to toxic heavy metal release into the soil and water. Agricultural runoff in rural areas introduces reactive nitrogen and sulfur compounds. The interplay between land use, climatic differences, and industrial expansion has further shaped regional contamination patterns. Inadequate waste management and weak environmental regulations exacerbate pollution, particularly in rapidly urbanizing regions. This regional complexity underscores the importance of targeted interventions, particularly in urban and peri-urban areas where industrial and vehicular emissions are the most significant contributors to contamination.

Our meta-analysis of heavy metal contamination in crops and fish revealed substantial contamination across several food sources. Cocoa, for example, exhibited elevated levels of copper (48.67 mg kg^{-1}), lead (70.03 mg kg^{-1}), and iron (41.60 mg kg^{-1}), while fish showed significant contamination with lead (5.97 mg kg^{-1}) and iron (156.39 mg kg^{-1}). Vegetables such as lettuce and onions displayed moderate contamination with lead (2.98 mg kg^{-1} and 2.28 mg kg^{-1}) and cadmium (5.18 mg kg^{-1} and 4.84 mg kg^{-1}), while maize and millet had relatively low lead

Table 8 Chronological records of heavy metal contamination in crops and food in Ghana

Year	Study/source	Location	Crop/food type	Season of measurement	Non-point sources	Key findings
2005–2022	42	Sekondi-Takoradi Metropolitan and Accra, Tamale and Navrongo, Ghana	Fresh leafy vegetable	Review	Review	Found that iron concentrations in *Amaranthus spinosus* (36.178 mg kg^{-1}) and *Corchorus olitorius* (27.587 mg kg^{-1}) are notably high and may exceed safe thresholds when compared to typical limits in similar studies. In Tamale and Navrongo, cadmium and chromium in leafy greens exceeded safe limits, with hazard indices over 1, indicating health risks. Wastewater-irrigated lettuce in Accra showed high cadmium (1.1 mg kg^{-1}), chromium (1.1 mg kg^{-1}), zinc (10.6 mg kg^{-1}), copper (6.3 mg kg^{-1}), and lead (10.2 mg kg^{-1}) levels, posing a health concern
2007	89	Medina, in Accra, Medoma in Kumasi, Tunsuom in Mampong and Adidwan, a rural setting, Ghana	Soil and plant	February to April	N/A	Found concentration ranges of heavy metals in soils and plants, including critical levels. Cadmium (Cd) ranges from 0.01–2 μg g^{-1} in soils and 0.1–2.4 μg g^{-1} in plants, critical at 5–30 μg g^{-1}. Mercury (Hg) is 0.01–0.5 μg g^{-1} in soils and 0.005–0.17 μg g^{-1} in plants, critical at 1–3 μg g^{-1}. Lead (Pb) ranges from 2–300 μg g^{-1} in soils and 0.2–20 μg g^{-1} in plants, with a critical level of 30–300 μg g^{-1}. Other metals also have specified ranges and critical levels
2017	43	Tamale Aboabo Market in the Northern Region of Ghana	Cereals and legumes	December	N/A	Found that arsenic levels exceeded safe limits in both rice (0.10–0.20 mg kg^{-1}) and legumes such as cowpea, soybean, and groundnuts (0.049–0.083 mg kg^{-1}), while copper was detected in all cereals and legumes but remained within safe levels. Lead and cadmium were not detected in any of the samples, and zinc concentrations were also found to be within acceptable limits
2019	44	Tolon District, northern region of Ghana	Maize and millet	March	N/A	Found that the heavy metal levels in maize and millet were within acceptable limits, except for lead (Pb), which exceeded the 0.2 mg kg^{-1} standard (2.22 mg kg^{-1} for maize and 2.28 mg kg^{-1} for millet). Nickel (Ni) and manganese (Mn) were below permissible limits (10 mg kg^{-1} and 2.3 mg kg^{-1}, respectively). Iron (Fe), chromium (Cr), and zinc (Zn) levels were also safe for consumption
2020	45	Korle lagoon, Tema Newtown fishing market, Ghana	Fish	February	N/A	Fish from Korle Lagoon and Tema Newtown market showed high levels of zinc (up to 12370.88 μg kg^{-1}), copper (up to 773.65 μg kg^{-1}), and mercury (up to 156.39 μg kg^{-1}), exceeding safe limits, with potential health risks for consumers

Table 8 (*Contd.*)

Year	Study/source	Location	Crop/food type	Season of measurement	Non-point sources	Key findings
2023	90	Ghana	Fruits and vegetables	Review	Review	Found that heavy metals, including cadmium, arsenic, chromium, and lead, are key contaminants in Ghana's fruit and vegetable industry, mainly from fresh manure and contaminated irrigation water. It recommends thorough washing of produce, soil remediation, and establishing traceability systems to enhance food safety
2024	46	Abuakwa North Municipality of Eastern Region, Ghana	Soil samples (0–15 and 15–30 cm) and cocoa pods	Cocoa season	Cocoa season	Found that cocoa beans from Kukurantumi had the highest copper (48.67 mg kg^{-1}) and cadmium (0.203 mg kg^{-1}) concentrations, while Tafo had the highest iron (41.60 mg kg^{-1}) and zinc (70.03 mg kg^{-1}) levels. Lead concentrations were consistently low across all communities. The variations indicate environmental influences on heavy metal levels in cocoa cultivation
2024	47	Kwame Nkrumah University of Science and Technology (KNUST) and its environs	Lettuce and spring onions	March	N/A	Found that arsenic (As): all samples (farms A, B, C, and market) exceed the RML of 0.1 mg kg^{-1}. Cadmium (Cd): all samples exceed the RML of 0.2 mg kg^{-1}. Chromium (Cr): most samples exceed the RML of 2.3 mg kg^{-1}, with some showing much higher concentrations. Mercury (Hg): all samples exceed the RML of 0.01 mg kg^{-1}. Manganese (Mn): all samples are below the RML of 500 mg kg^{-1}. Nickel (Ni): all samples are below the RML of 67.9 mg kg^{-1}. Lead (Pb): most samples exceed the RML of 0.3 mg kg^{-1}
2024	48	Haatso, Dzorwulu and the Weija irrigation scheme site	Fresh lettuce and bell pepper	Growing season	N/A	Found high mercury levels in lettuce: 360 μg kg^{-1} (Haatso), 1160 μg kg^{-1} (Dzorwulu), and 4860 μg kg^{-1} (WISS), exceeding the WHO limit of ≤1000 μg kg^{-1}. Lead (50 μg kg^{-1}) and cadmium (30 μg kg^{-1}) were within safe limits. In pepper, mercury levels were also elevated: 150 μg kg^{-1} (Haatso), 280 μg kg^{-1} (Dzorwulu), and 3090 μg kg^{-1} (WISS), all surpassing the WHO standard. Lead and cadmium levels in pepper remained safe at 50 μg kg^{-1} and 30 μg kg^{-1}, respectively
2024	91	Gulf of Guinea at James Town in Ghana	Cassava fish, flatfish, Redfish, kingfish, and silverfish, and sediment	N/A	N/A	Found that lead (Pb) and cadmium (Cd) concentrations in silver fish gills were significantly elevated, with Pb at 5.97 mg kg^{-1} and Cd at 14.11 mg kg^{-1}, exceeding WHO standards. Sediment also had high Pb levels (4.91 mg kg^{-1}). Manganese (Mn) was notably high in silver fish gills (12.82 mg kg^{-1}) and sediment (26.61 mg kg^{-1}), while mercury (Hg) and arsenic (As) were not detected

Table 9 Chronological records of airborne heavy metal and sulfur deposition across Ghana

Year	Location	Type of dust	Heavy metals detected	Reactive nitrogen detected	Sulfur detected	Elemental concentrations			Source/study
2005 to 2006	Kwabenya, Accra, Ghana	PM2.5–10	Mn, Zn, Cu, Pb and Cr	N/A	S: 463.8 ng m^{-3}	S: 463.8 ng m^{-3}, Mn: 33.04 ng m^{-3}, Zn: 11.8 ng m^{-3}, Cr: 6.9 ng m^{-3}, Cu: 2.4 ng m^{-3}, and Pb: 3 ng m^{-3}			18
2006 to 2007	Kwabenya, Accra, Ghana	PM2.5–10	Mn, Ni, Cu, Zn, Cr, and Pb	N/A	S: 1310, 319, 524, 442 ng m^{-3}		PM2.5–10 Harmattan	Non-Harmattan	29
						S (ng m^{-3})	1310	319	
						Cr con:	16.9	—	
						Mn con:	279	17.7	
						Ni con:	18	3.2	
						Cu con:	22.4	4.4	
						Zn con:	59.8	7.6	
						Pb con:	21.8	2.7	
							PM2.5 Harmattan	Non-Harmattan	
						S Con:	524	442	
						Mn con:	19	3.5	
						Ni con:	6.1	2.3	
						Cu con:	6.9	3.2	
						Zn con:	9.5	5.5	
						Pb con:	3.5	2.1	
2008	James Town/Usher Town (JT/UT) and Nima, Accra, Ghana	PM2.5, PM10 and PM2.5–10	Mn, Cu, Zn, and Pb	NO_2 (21.03 ppm) in Nima	S: 1412.6, 982.5 and 1412.5 ng m^{-3}		PM10	PM2.5	53
						S (ng m^{-3})	1412.5	982.5	
						Mn con:	30.5	7.5	
						Cu con:	10	6.5	
						Pb con:	24.5	15.5	
						Zn con:	65.5	31	
September 2007 and August 2008	James Town/Usher Town (JT), Asylum Down (AD), Nima (NM) and East Legon (EL)	PM2.5, PM10 and TSP	Cr, Ni, Cu, Zn and Pb	N/A	N/A		PM10	M2.5	30
						Cr con: (ng m^{-3})	4.0	1.4	
						Ni con:	3.0	3.4	
						Cu con:	8.2	4.8	
						Zn con:	49.2	31.8	
						Pb con:	21.0	15.6	
November to December, 2011	Accra – Tema highway in Ghana	Ambient air	As, Ni, Pb, Cr, and Cd	N/A	N/A	As: 0.059 µg m^{-3}, Cr: 0.115 µg m^{-3}, Ni: 0.218 µg m^{-3}, Cd: 0.007 µg m^{-3} and Pb: 0.011 µg m^{-3}			54

Table 10 Chronological records of reactive nitrogen, sulfate, and heavy metals in rainwater in Ghana

Year	Location	Type of dust/ rainfall	Heavy metals detected	Reactive nitrogen detected	Sulfur detected	Concentration levels	Source/ study
1997 and 1998 rainy seasons	Tamale	Rainy season	N/A	NO_3^- > 0.3 mg L^{-1})	SO_4^{2-} (0.43–6.7)	SO_4^{2-} concentrations are significantly higher than NO_3^- levels, with SO_4 ranging from 0.43 mg L^{-1} to 6.7 mg L^{-1} and NO_3 typically below 0.3 mg L^{-1}. The SO_4^{2-}/Cl^- ratio varies between 0.36 and 1.79, indicating substantial variability in sulfate contamination relative to chloride	55
May to September in 2007	Ramia, Wawasi and Antobuasi in Obuasi, a gold Mining town in Ghana	Peak of the rainy season	Pb: 0.15–0.19 mg L^{-1} across sites, Cd: non-detectable to 0.1 mg L^{-1}, and Zn: 0.01–0.12 mg L^{-1} across all sites	NO_3^-: ranges: 0.11–0.32 mg L^{-1} (Ramia), 0.01–0.42 mg L^{-1} (Antobuasi), and 0.09–0.32 mg L^{-1} (Wawasi)	SO_4^{2-}: ranges: 11.0–12.82 mg L^{-1} (Ramia), 10.22–12.45 mg L^{-1} (Antobuasi), and 8.90–11.80 mg L^{-1} (Wawasi)	pH: ranges: 4.4–5.6 (Ramia), 4.1–4.9 (Antobuasi), and 4.0–5.4 (Wawasi). Cl^-: ranges: 4.25–6.22 mg L^{-1} (Ramia), 3.22–5.16 mg L^{-1} (Antobuasi), and 4.0–4.65 mg L^{-1} (Wawasi). The rainwater analysis shows low concentrations of NO_3 (0.01–0.42 mg L^{-1}), moderate levels of SO_4 (8.90–12.82 mg L^{-1}), and stable Cl^- levels (3.22–6.22 mg L^{-1}) across all sites. The pH values (4.0–5.6) indicate acidic rain, suggesting possible environmental concerns related to acid deposition in the area. The rainwater analysis showed high levels of lead, cadmium, iron, and zinc, with lead exceeding the WHO limit, posing environmental and health risks	58
Rainy and dry season 2013	Tamale	Rainy and dry seasons	N/A	NO_3^-: ranges 0.01–6.5 mg L^{-1}	SO_4^{2-} (0.04–8.2 mg L^{-1})	pH: 5.02–9.0; SO_4^{2-} concentrations are significantly higher than NO_3^- levels, with SO_4 ranging from 3.73 mg L^{-1} and NO_3 typically below 1.58 mg L^{-1}. The Cl^- was 3.57	56
February and March, 2014	Ayanfuri in the Upper Denkyira West District, Central Region of Ghana	Feb. and March rainfall	Mn: −0.03–0.52 mg L^{-1}, Pb: 0.14–0.36 mg L^{-1}, and Cd: −0.38–0.30 mg L^{-1}	NO_3^-: ranges 0.46–2.23 mg L^{-1}	SO_4^{2-}: 11.53–18.36 mg L^{-1}	pH: 5.88–7.01; Cl^-: 2.00–6.01 mg L^{-1}. These findings highlight that while pH, NO_3, SO_4, and Cl^- concentrations are within safe limits, the levels of Pb and Cd in the rainwater are alarmingly higher than WHO guidelines, posing a risk to water quality and safety	57

levels (2.22 mg kg^{-1} and 2.28 mg kg^{-1}). Additionally, *Amaranthus spinosus* and *Corchorus olitorius* presented potential health risks due to elevated iron contamination (36.18 mg kg^{-1} and 27.59 mg kg^{-1}). These findings are consistent with previous studies[42–47] and highlight the need for improved food safety measures in Ghana to reduce risks linked to industrial, vehicular, and mining pollution. The contamination of the food chain underscores an urgent need for strengthened agricultural monitoring and consumer safety measures.

Our meta-analysis of rainwater contamination in Ghana examined pH levels and pollutant deposition. Sulfate emerged as the dominant pollutant, with the highest concentrations recorded in the Central region (50.30%), followed by the Southern (36.94%) and Northern regions (12.77%). Nitrate concentrations were highest in the Northern region (53.28%), while acidic rain (pH < 6.5) was more prevalent in Southern and Central Ghana. Mining hotspots such as Obuasi and Ayanfuri showed elevated levels of lead and cadmium contamination in rainwater (Table 4). Increasing sulfate and heavy metal deposition in rainwater could compound soil acidification and water quality challenges, necessitating integrated management approaches. The observed rainwater contamination trends are primarily influenced by industrial emissions, which contribute to sulfate pollution, especially in urban areas. Agricultural activities lead to the accumulation of nitrate in northern Ghana. Mining operations release lead and cadmium into the atmosphere, resulting in rainwater contamination. These findings support earlier research that highlights sulfate dominance in Tamale (1997–2013) and Ayanfuri (2014), as well as significant heavy metal contamination in Obuasi and Ayanfuri.[55–58] Mining, industrial pollution, and agricultural runoff continue to be major contributors to rainwater contamination across Ghana. This underscores the need for strengthening regulations and the adoption of cleaner technologies in the mining and industrial sectors to reduce environmental contamination in vulnerable regions.

5.1 Study limitations

Despite providing a comprehensive meta-analysis and synthesis of environmental contamination in Ghana, this study has several limitations. First, data availability was uneven across regions, particularly with limited studies from the Central region, which constrained regional comparisons. Second, the meta-analysis relied on secondary data from heterogeneous sources with varying methodologies, sampling periods, and detection limits, which may introduce biases or inconsistencies. Additionally, the lack of standardized reporting across studies meant that some data especially standard errors and detection limits were unavailable or omitted. Finally, while efforts were made to present national-level trends, the scarcity of stratified data from urban, peri-urban, and rural zones limited fine-scale spatial analyses. Although temporal trends were observed, data gaps and inconsistent methodologies constrain definitive conclusions about long-term changes in pollutant levels. Future research should prioritize harmonized monitoring protocols and the collection of high-resolution, georeferenced data to address these gaps.

6. Conclusion

This systematic review provides important insights into the environmental pollution challenges confronting Ghana, highlighting the complex dynamics of airborne dust deposition, particulate matter, and heavy metal contamination. The observed regional disparities in pollution levels emphasize the need for targeted, site-specific interventions to effectively mitigate these risks. The accumulation of heavy metals in agricultural systems, particularly in crops and fish, poses a significant threat to food safety, agricultural productivity, and, ultimately, food security in Ghana. By integrating meta-analytic data from multiple environmental media, including air, water, soil, and food sources, this study offers a comprehensive understanding of pollutant interactions and their impacts on ecosystems. The findings underscore the urgency of implementing stronger environmental policies and regulations, along with promoting sustainable practices in both urban and rural settings. These proactive measures are essential to address the growing environmental and public health challenges. Overall, this review contributes to the critical discourse on atmospheric pollution in West Africa and calls for coordinated efforts to safeguard human health and ecosystem integrity.

6.1 Future perspectives and broader context

Building on the findings of this study, there is a clear need to establish long-term, regionally coordinated monitoring systems that can systematically track pollution levels and assess their environmental and health impacts across Ghana and the broader West African region. Such monitoring will provide essential data to inform timely and effective responses. Future research should focus on evaluating the effectiveness of targeted mitigation strategies, especially those aimed at reducing heavy metal contamination in soil, water, and food crops, thereby ensuring food safety and security. Moreover, the development of evidence-based regional policies is critical. These policies should incorporate stringent environmental regulations and promote cleaner industrial and mining practices. Special attention must be given to protecting vulnerable populations, particularly those residing in mining and urban areas, through enhanced waste management and pollution control measures. By offering clear, data-driven guidance, these recommendations aim to support policymakers, local communities, and industries in implementing sustainable interventions that safeguard public health and foster environmental resilience.

Ethical responsibilities of authors

All authors have read, understood, and agreed to the ethical standards and guidelines outlined for the research, ensuring integrity and compliance with ethical principles.

Declaration

This review followed the PRISMA 2020 guidelines. No protocol was registered for this review.

Data availability

The data supporting the findings of this study are included within the article in the form of summarized tables. Additional details can be obtained from the corresponding author upon reasonable request.

Author contributions

Zikrullah Safi contributed to the methodology, data collection, and writing of the original draft. Professor Michael Miyittah, Dr Godwin Amenorpe, and Benjamin Kwasi Offei provided critical revisions and ensured the overall integrity of the manuscript. All authors participated in the final manuscript preparation and approved the final version.

Conflicts of interest

The authors declare no competing interests. There are no financial or personal relationships that could influence the work presented in this manuscript.

Acknowledgements

The authors are grateful to the anonymous reviewers for their insightful comments and suggestions, which greatly contributed to improving the quality and clarity of this manuscript. We also acknowledge the support of the Alexander von Humboldt Stiftung, which helped facilitate this work.

References

1 C. R. Lawrence and J. C. Neff, The contemporary physical and chemical flux of aeolian dust: A synthesis of direct measurements of dust deposition, *Chem. Geol.*, 2009, **267**(1–2), 46–63, DOI: 10.1016/j.chemgeo.2009.02.005.

2 C. He, H. Breuning-Madsen and T. W. Awadzi, Mineralogy of dust deposited during the Harmattan season in Ghana, *Geogr. Tidsskr. Dan. J. Geogr.*, 2007, **107**(1), 9–15, DOI: 10.1080/00167223.2007.10649523.

3 H. Breuning-Madsen, T. W. Awadzi and G. Lyngsie, Deposition of nutrients from Harmattan dust in Ghana, West Africa, *Pedosphere*, 2015, **25**(4), 613–621, DOI: 10.1016/S1002-0160(15)30041-2.

4 Z. Safi and A. Buerkert, Heavy metal and microbial loads in sewage irrigated vegetables of Kabul, Afghanistan, *J. Agric. Res. Trop. Subtrop.*, 2011, **112**(1), 29–36.

5 N. Abdu, J. O. Agbenin and A. Buerkert, Fractionation and mobility of cadmium and zinc in urban vegetable gardens of Kano, northern Nigeria, *Environ. Monit. Assess.*, 2012, **184**(4), 2057–2066, DOI: 10.1007/s10661-011-2099-2.

6 N. N. Karanja, M. Njenga, G. K. Mutua, C. J. Lagerkvist, E. Kutto and J. J. Okello, Concentrations of heavy metals and pesticide residues in leafy vegetables and implications for peri-urban farming in Nairobi, Kenya, *J. Agric. Food Syst. Community Dev.*, 2012, **3**(1), 255–267, DOI: 10.5304/jafscd.2012.031.003.0.

7 N. Abdu, J. Agbenin and A. Buerkert, Phytoavailability, human risk assessment and transfer characteristics of cadmium and zinc contamination from urban gardens in Kano, Nigeria, *J. Sci. Food Agric.*, 2011, **91**(15), 2722–2730, DOI: 10.1002/jsfa.4583.

8 N. Abdu, A. Abdulkadir, J. Agbenin and A. Buerkert, Vertical distribution of heavy metals in wastewater-irrigated vegetable garden soils of three West African cities, *Nutr. Cycl. Agroecosyst.*, 2011, **89**, 387–397.

9 W. Colglazier, Sustainable development agenda: 2030, *Science*, 2015, **349**, 1048–1050, DOI: 10.1126/science.aad2333.

10 H. Nagendra, X. Bai, E. S. Brondizio and S. Lwasa, The urban south and the predicament of global sustainability, *Nat. Sustain.*, 2018, **1**, 341–349, DOI: 10.1038/s41893-018-0033-3.

11 C. B. d'Amour, F. Reitsma, G. Baiocchi, S. Barthel, B. Güneralp, K. H. Erb, H. Haberl, F. Creutzig and K. C. Seto, Future urban land expansion and implications for global croplands, *Proc. Natl. Acad. Sci. U. S. A.*, 2017, **114**, 8939–8944, DOI: 10.1073/pnas.1606036114.

12 B. Güneralp, M. Reba, B. U. Hales, E. A. Wentz and K. C. Seto, Trends in urban land expansion, density, and land transitions from 1970 to 2010: A global synthesis, *Environ. Res. Lett.*, 2020, **15**, 044015, DOI: 10.1088/1748-9326/ab6669.

13 Z. Safi, M. Predotova, E. Schlecht and A. Buerkert, Horizontal matter fluxes and leaching losses in urban agriculture of Kabul, Afghanistan, *J. Plant Nutr. Soil Sci.*, 2011, **174**, 942–951, DOI: 10.1002/jpln.201000385.

14 D. J.-P. Lompo, S. A.-K. Sangaré, E. Compaoré, M. P. Sedogo, M. Predotova, E. Schlecht and A. Buerkert, Gaseous emissions of nitrogen and carbon from urban vegetable gardens in Bobo-Dioulasso, Burkina Faso, *J. Plant Nutr. Soil Sci.*, 2012, **175**, 846–853, DOI: 10.1002/jpln.201200012.

15 D. Manka'abusi, D. J.-P. Lompo, C. Steiner, M. Ingold, E. K. Akoto-Danso, S. Werner, V. Häring, G. Nyarko, B. Marschner and A. Buerkert, Carbon dioxide and gaseous nitrogen emissions from biochar-amended soils under wastewater irrigated urban vegetable production of Burkina Faso and Ghana, *J. Plant Nutr. Soil Sci.*, 2020, **183**, 567–578, DOI: 10.1002/jpln.201900183.

16 W. Winiwarter, B. Amon, Z. Bai, A. Greinert, K. Kaltenegger, L. Ma, S. Myszograj, M. Schneidergruber, M. Suchowski-Kisielewicz, L. Wolf, L. Zhang and F. Zhou, Urban nitrogen budgets: flows and stock changes of potentially polluting nitrogen compounds in cities and their surroundings - a review, *J. Integr. Environ. Sci.*, 2020, **17**, 57–71, Available from: https://gepris.dfg.de/gepris/projekt/20025697, http://www.urbanfoodplus.org, http://www.uni-kassel.de/go/for-2432, http://www.uni-kassel.de/go/pro-ruwa.

17 A. Sunnu, G. Afetia and F. Resch, A long-term experimental study of the Saharan dust presence in West Africa, *Atmos. Res.*, 2008, **87**(1), 13–26, DOI: 10.1016/j.atmosres.2007.07.001.

18 I. J. K. Aboh and F. G. Ofosu, The determination of mass, element, and black carbon concentrations in Harmattan aerosol samples collected at Kwabenya, Ghana, *J. Ghana Sci. Assoc.*, 2010, **12**(2), 64–65.

19 A. S. Alli, S. N. Clark, A. Hughes, J. Nimo, J. Bedford-Moses, S. Baah, J. Wang, J. Vallarino, E. Agyemang, B. Barratt, A. Beddows, F. Kelly, G. Owusu, J. Baumgartner, M. Brauer, M. Ezzati, S. Agyei-Mensah and R. E. Arku, Spatial-temporal patterns of ambient fine particulate matter (PM2.5) and black carbon (BC) pollution in Accra, *Environ. Res. Lett.*, 2021, **16**(7), 074013, DOI: **10.1088/1748-9326/ac074a**.

20 C. K. Klutse, M. A. Quayson, A. Forson, E. A. Asare and C. Nuveadenu, The effect of e-waste recycling on metal and metalloid prevalence in soil: A case study from Ghana, *Environ. Monit. Assess.*, 2023, **195**(2), 456, DOI: **10.1007/s10661-023-12223-4**.

21 P. A. Opoku, G. K. Anornu, A. Gibrilla, E. D. G. J. Owusu-Ansah, S. Y. Ganyaglo and C. D. Egbi, Spatial distributions and probabilistic risk assessment of exposure to heavy metals in groundwater in a peri-urban settlement: case study of Atonsu-Kumasi, Ghana, *Groundwater Sustain. Dev.*, 2020, **10**, 100327, DOI: **10.1016/j.gsd.2020.100327**.

22 Groundwater for Sustainable Development, Erratum regarding missing Declaration of Competing Interest statements in previously published articles, *Groundwater Sustain. Dev.*, 2021, **13**, 100596, DOI: **10.1016/j.gsd.2021.100596**.

23 S. Hoffmann, R. B. de Vries, M. L. Stephens, N. B. Beck, H. A. Dirven, J. R. Fowle, *et al.*, A primer on systematic reviews in toxicology, *Arch. Toxicol.*, 2017, **91**(11), 2551–2575, DOI: **10.1007/s00204-017-1980-3**.

24 M. J. Page, J. E. McKenzie, P. M. Bossuyt, I. Boutron, T. C. Hoffmann, C. D. Mulrow, L. Shamseer, J. M. Tetzlaff, E. A. Akl, S. E. Brennan, R. Chou, J. Glanville, J. M. Grimshaw, A. Hróbjartsson, M. M. Lalu, T. Li, E. W. Loder, E. Mayo-Wilson, S. McDonald and D. Moher, The PRISMA 2020 statement: An updated guideline for reporting systematic reviews, *PLoS Med.*, 2021, **18**(3), e1003583, DOI: **10.1371/journal.pmed.1003583**.

25 H. Breuning-Madsen, G. Lyngsie and T. W. Awadzi, Determination of dust deposition and associated nutrients in natural forest and plantation—A case study from the moist semi-deciduous forest zone in Ghana, *Geoderma*, 2017, **285**, 240–246, DOI: **10.1016/j.geoderma.2016.10.026**.

26 M. E. Emetere, L. Onyechekwa and P. T. Olayeni, Atmospheric configurations of aerosols loading and retention over Bolgatanga-Ghana, *J. Phys.: Conf. Ser.*, 2017, **852**, 012007, DOI: **10.1088/1742-6596/852/1/012007**.

27 V. Adu-Gyamfi, S. J. Cobbina, S. B. Dampare and A. B. Duwiejuah, Heavy metals concentration in road dust in the Bolgatanga Municipality, Ghana, *J. Environ. Pollut. Hum. Health*, 2014, **2**(4), 74–80, DOI: **10.12691/jephh-2-4-1**.

28 P. B. Awuah, A. A. Adjaottor, E. Gikunoo, E. K. Arthur, F. O. Agyemang and D. S. Baah, Dust deposition and associated heavy metal contamination in the neighborhood of a cement production plant at Konongo, Ghana, *J. Chem.*, 2022, **2022**, 6370679, DOI: **10.1155/2022/6370679**.

29 I. J. K. Aboh, D. Henriksson, J. Laursen, M. Lundin, F. G. Ofosu, N. Pind, E. Selin Lindgren and T. Wahnström, Identification of aerosol particle sources in semi-rural area of Kwabenya, near Accra, Ghana, by EDXRF techniques, *X-Ray Spectrom.*, 2009, **38**(4), 348–353, DOI: **10.1002/xrs.1172**.

30 Z. Zhou, K. L. Dionisio, T. G. Verissimo, A. S. Kerr, B. Coull, R. E. Arku, P. Koutrakis, J. D. Spengler, A. F. Hughes, J. Vallarino, S. Agyei-Mensah and M. Ezzati, Chemical composition and sources of particle pollution in affluent and poor neighborhoods of Accra, Ghana, *Environ. Res. Lett.*, 2013, **8**(4), 044025, DOI: **10.1088/1748-9326/8/4/044025**.

31 F. Krampah, N. Amegbey, S. Ndur, Y. Y. Ziggah and P. K. Hopke, Fractal analysis and interpretation of temporal patterns of TSP and PM10 mass concentration over Tarkwa, Ghana, *Earth Syst. Environ.*, 2021, **5**(3), 635–654, DOI: **10.1007/s41748-021-00237-2**.

32 J. Bahino, M. Giordano, M. Beekmann, V. Yoboué, A. Ochou, C. Galy-Lacaux, C. Liousse, A. Hughes, J. Nimo, F. Lemmouchi, J. Cuesta and R. Subramanian, Temporal variability and regional influences of PM2.5 in the West African cities of Abidjan (Côte d'Ivoire) and Accra (Ghana), *Environ. Sci.: Atmos.*, 2024, **4**, 468, DOI: **10.1039/d4ea00012a**.

33 P. A. Gyasi, J. N. O. Amu-Darko, E. Issaka and E. N. A. Amarteifio, Air pollution and health: Particulate matter PM2.5 measurements in Cantonments, Ghana, *EPRA Int. J. Multidiscip. Res.*, 2022, **8**, 1–8, DOI: **10.36713/epra11460**.

34 K. Kodom, K. Preko and D. Boamah, X-ray fluorescence (XRF) analysis of soil heavy metal pollution from an industrial area in Kumasi, Ghana, *Soil Sediment Contam.*, 2012, **21**, 1006–1021, DOI: **10.1080/15320383.2012.712073**.

35 F. Obiri-Nyarko, E. Manu, A. A. Duah, R. Tagoe, A. Y. Karikari and W. A. Agyekum, Assessment of heavy metal contamination in soils at the Kpone landfill site, Ghana: Implication for ecological and health risk assessment, *Chemosphere*, 2021, **282**, 131007, DOI: **10.1016/j.chemosphere.2021.131007**.

36 G. Edusei, J. B. Tandoh, R. Edziah, O. Gyampo and H. Ahiamadjie, Chronological study of metallic pollution using tree rings at Tema industrial area, *Pollution*, 2021, **7**(1), 197–204, DOI: **10.22059/poll.2020.306742.855**.

37 G. Edusei, C. Subaar, E. Gyan, J. Osei-Owusu, R. Edziah, A. K. Dofuor, J. B. Tandoh, R. Kwakye and E. Ntim, Determination of heavy metals pollution in soil and tree rings along Haatso-Atomic Road in Ghana, *J. Pollut. Eff. Comm. Health*, 2022, **1**(1), 002, DOI: **10.58489/2836-3590/002**.

38 E. Bessah, A. Strapasson, E. Donkor, A. O. Rajic, O. J. Taiwod, S. K. Agodzo and O. O. Ololade, Assessment of surface waters and pollution impacts in Southern Ghana, *Hydrol. Res.*, 2021, **52**(6), 1423, DOI: **10.2166/nh.2021.051**.

39 B. D. Asamoah, M. Dodd, L. L. Yevugah, L. S. Borquaye, A. Boateng, M. A. Nkansah and G. Darko, Distribution and in vitro bioaccessibility of potentially toxic metals in surface soils from a mining and a non-mining community in Ghana: Implications for human health, *Environ. Geochem. Health*, 2023, **45**, 9875–9889, DOI: **10.1007/s10653-023-01776-5**.

40 World Health Organization, *Guidelines for Drinking-Water Quality: Fourth Edition Incorporating the First Addendum*,

World Health Organization, Geneva, 2017, Licence: CC BY-NC-SA 3.0 IGO, Available from: **https://apps.WHO.Int/iris/Handle/10665/254637**.

41 Ministry of the Environment, Finland, *Government Decree on the Assessment of Soil Contamination and Remediation Needs (214/2007, March 1, 2007)*, 2007.

42 P. Atitsogbey, E. Kyereh, M. Steiner-Asiedu, H. Ofori and P.-N. T. Johnson, Heavy metal, microbial, and pesticide residue contaminations limiting the potential consumption of green leafy vegetables in Ghana: An overview, *Heliyon*, 2023, **9**, e15466, DOI: **10.1016/j.heliyon.2023.e15466**.

43 A. A. Adama, L. N. A. Sackey and L. A. Ofori, Risk assessment of heavy metals concentration in cereals and legumes sold in the Tamale Aboabo market, Ghana, *Heliyon*, 2022, **8**, e10162, DOI: **10.1016/j.heliyon.2022.e10162**.

44 K.-V. Larsen, S. J. Cobbina and S. A. Ofori, Quantification and health risk assessment of heavy metals in milled maize and millet in the Tolon District, Northern Ghana, *Food Sci. Nutr.*, 2020, **8**(12), 6419–6429, DOI: **10.1002/fsn3.1714**.

45 S. L. Steinhausen Vazquez, N. Agyeman, P. Turrero, A. Ardura and E. Garcia, Heavy metals in fish nearby electronic waste may threaten consumers' health: Examples from Accra, Ghana, *Mar. Pollut. Bull.*, 2022, **175**, 113162, DOI: **10.1016/j.marpolbul.2022.113162**.

46 S. Yeboah, J. A. Dogbatse, M. A. Kumi, R. X. Supe Tulcan and L. Addae-Wireko, Heavy metal status in cocoa (Theobroma cacao L.) soils and beans: The case of Abuakwa North Municipality of Eastern Region, Ghana, *Environ. Monit. Assess.*, 2024, **196**, 156, DOI: **10.1007/s10661-024-12334-6**.

47 L. N. A. Sackey, K. Markin, A. Kwarteng, I. M. Ayitey and P. Kayoung, Presence and levels of potential trace elements in lettuce and spring onion grown in Kumasi, Ghana, *Kuwait J. Sci.*, 2024, **51**, 100143, DOI: **10.1016/j.kjs.2024.100143**.

48 S. F. Gbedemah, L. K. Frimpong, A. A. Gbeasor, R. Amfo-Otu, G. S. Hosu-Porbley, S. K. Adanu and E. K. Doe, Analysis of heavy metals and pathogen levels in vegetables cultivated using selected water bodies in urban areas of the Greater Accra Metropolis of Ghana, *Heliyon*, 2024, **10**, e27924, DOI: **10.1016/j.heliyon.2024.e27924**.

49 Codex Alimentarius Commission, *General Standard for Contaminants and Toxins in Food and Feed (CXS 193-1995). Adopted 1995, Revised 1997, 2006, 2008, 2009; Amended 2010–2023*, Food and Agriculture Organization of the United Nations & World Health Organization, Available from: **https://www.fao.org/fao-who-codexalimentarius**.

50 USEPA, Risk Assessment Guidance for Superfund, in *Human Health Evaluation Manual (Part A), Report EPA/540/1-89/002*, United States Environmental Protection Agency, Washington, DC, USA, 1989, vol. 1.

51 World Health Organization (WHO), Toxicological evaluation of certain food additives and contaminants, *Report of the 33rd Meeting, Joint FAO/WHO Expert Committee on Food Additives. No. 24, International Programme on Chemical Safety*, WHO, Geneva, 1989.

52 I. J. K. Aboh, *Characterization and Sources of Air Particulate Matter at Kwabenya, Near Accra, Ghana Dissertation. Legon*, University of Ghana, 2009.

53 R. E. Arku, J. Vallarino, K. L. Dionisio, R. Willis, H. Choi, J. G. Wilson, *et al.*, Characterizing air pollution in two low-income neighborhoods in Accra, Ghana, *Sci. Total Environ.*, 2008, **402**(2–3), 217–231, DOI: **10.1016/j.scitotenv.2008.04.042**.

54 G. Safo-Adu, F. G. Ofosu, D. Carboo and Y. S. Armah, Heavy metals and black carbon assessment of PM10 particulates along Accra–Tema highway in Ghana, *Int. J. Sci. Technol.*, 2014, **3**(8), 467–474.

55 K. B. Pelig-Ba, A. Parker and M. Price, *Elemental Contamination of Rainwater by Airborne Dust in Tamale Township Area of the Northern Region of Ghana*, Postgrad Res Inst Sedimentol, Univ Reading, P.O. Box 227, RG6 6AB Reading, England, 2001.

56 S. J. Cobbina, K. Michael, L. Salifu and A. B. Duwiejua, Rainwater quality assessment in the Tamale Municipality, *Int. J. Sci. Technol. Res.*, 2013, **2**(5), 227–8616.

57 N. Amponsah, N. Bakobie, S. J. Cobbina and A. B. Duwiejuah, Assessment of rainwater quality in Ayanfuri, Ghana, *Am. Chem. Sci. J.*, 2015, **6**(3), 172–182, DOI: **10.9734/ACSj/2015/15881**.

58 O. Akoto, G. Darko and M. A. Nkansah, Chemical composition of rainwater over a mining area in Ghana, *Int. J. Environ. Res.*, 2011, **5**, 847–854.

59 D. Orange, J. Y. Gac and M. I. Diallo, Geochemical assessment of atmospheric deposition including Harmattan dust in continental West Africa, in *Tracers in Hydrology, Proceedings of the Yokohama Symposium, July 1993, IAHS Publ. No. 215*, International Association of Hydrological Sciences, 1993.

60 H. Breuning-Madsen and T. W. Awadzi, Harmattan dust deposition and particle size in Ghana, *Catena*, 2005, **63**, 23–38.

61 F. Resch, A. Sunnu and G. Afeti, Saharan dust flux and deposition rate near the Gulf of Guinea, *Tellus B*, 2008, **60**, 98–105, DOI: **10.1111/j.1600-0889.2007.00286.x**.

62 T. W. Awadzi and H. Breuning-Madsen, Harmattan dust deposited in Ghana within 2000–2005, *West Afr. J. Appl. Ecol.*, 2007, **11**, 1–9, DOI: **10.4314/wajae.v11i1.45723**.

63 H. Breuning-Madsen, G. Lyngsie and T. W. Awadzi, Sediment and nutrient deposition in Lake Volta in Ghana due to Harmattan dust, *Catena*, 2012, **92**, 99–105.

64 F. G. Ofosu, I. K. J. Aboh and S. A. Bamford, Ambient air PM10 particulate levels at Ashaiman near Tema in Ghana, *Br. J. Appl. Sci. Technol.*, 2015, **15**, 1–9, DOI: **10.9734/BJAST/2016/19232**.

65 K. J. Bansah and N. Amegbey, Ambient particulate matter monitoring: A case study at Tarkwa, *Res. J. Environ. Earth Sci.*, 2012, **4**, 419–423.

66 M. S. Rooney, R. E. Arku, K. L. Dionisio, C. Paciorek, A. B. Friedman, H. Carmichael, Z. Zhou, A. F. Hughes, J. Vallarino, S. Agyei-Mensah, J. D. Spengler and M. Ezzati, Spatial and temporal patterns of particulate matter sources and pollution in four communities in Accra, Ghana, *Sci. Total Environ.*, 2012, **435–436**, 107–114, DOI: **10.1016/j.scitotenv.2012.07.013**.

67 A. K. Sunnu, G. Afeti and F. Resch, Daily levels of the Harmattan dust near the Gulf of Guinea over 15 years: 1996–2011, *Environ. Ecol. Res.*, 2018, **6**, 593–604, DOI: 10.13189/eer.2018.060609.

68 S. A. Sarpong, R. F. Donkoh, J. K. Konnuba, C. Ohene-Agyei and Y. Lee, Analysis of PM2.5, PM10, and total suspended particle exposure in the Tema metropolitan area of Ghana, *Atmosphere*, 2021, **12**, 700, DOI: 10.3390/atmos12060700.

69 E. K. P. Bam, T. T. Akiti, S. D. Osae, S. Y. Ganyaglo and A. Gibrilla, Multivariate cluster analysis of some major and trace elements distribution in an unsaturated zone profile, Densu river basin, Ghana, *Afr. J. Environ. Sci. Technol.*, 2011, **5**, 155–167, Available from: http://www.academicjournals.org/AJEST.

70 M. S. Atiemo, G. F. Ofosu, H. Kuranchie-Mensah, A. Osei Tutu, N. D. M. L. Palm and S. A. Blankson, Contamination assessment of heavy metals in road dust from selected roads in Accra, Ghana, *Res. J. Environ. Earth Sci.*, 2011, **3**, 473–480.

71 S. M. Atiemo, F. G. Ofosu, I. K. J. Aboh and O. C. Oppon, Levels and sources of heavy metal contamination in road dust in selected major highways of Accra, Ghana, *J. X-Ray Sci. Technol.*, 2012, **20**(1), 65–73, DOI: 10.1002/xrs.2374.

72 B. M. Tiimub, P. A. Sarkodie, I. Monney and O. Maxwell, Heavy metal contamination of soil by quarry dust at Asonomaso in the Ashanti Region of Ghana, *Chem. Mater. Res*, 2015, **7**, 1–8, Available from: http://www.iiste.org/Journals/index.php/CMR/article/view/24830.

73 A. Victoria, S. J. Cobbina, S. B. Dampare and A. B. Duwiejuah, Heavy metals concentration in road dust in the Bolgatanga municipality, Ghana, *J. Environ. Pollut. Hum. Health*, 2014, **2**, 74–80.

74 M. K. Dorleku, D. Nukpezah and D. Carboo, Effects of small-scale gold mining on heavy metal levels in groundwater in the Lower Pra Basin of Ghana, *Appl. Water Sci.*, 2018, **8**, 126, DOI: 10.1007/s13201-018-0773-z.

75 R. Appiah-Opong, A. Ofori, M. Ofosuhene, E. Ofori-Attah, F. K. E. Nunoo, I. Tuffour, C. Gordon, D. K. Arhinful, A. K. Nyarko and B. Y. Fosu-Mensah, Heavy metals concentration and pollution index (HPI) in drinking water along the southwest coast of Ghana, *Appl. Water Sci.*, 2021, **11**, 57, DOI: 10.1007/s13201-021-01386-5.

76 S. J. Cobbina, R. Yakubu, F. J. Akpabey, A. B. Duwiejuah and Z. N. Abuntori, Hydrochemistry of groundwater in the Tamale Metropolis, Ghana, *Environ. Earth Sci.*, 2021, **80**, 534, DOI: 10.1007/s12665-021-09882-2.

77 I. Lente, W. K. Heve, M. Y. Owusu-Twum, C. Gordon, P. Opoku, D. Nukpezah and R. Amfo-Otu, Assessing levels of selected heavy metals with other pollutants in soil and water resources in Nandom District in the semi-arid northwestern Ghana, *Environ. Monit. Assess.*, 2022, **194**, 919, DOI: 10.1007/s10661-022-10619-2.

78 G. Darko, M. Dodd, M. A. Nkansah, E. Ansah and Y. Aduse-Poku, Distribution and bioaccessibility of metals in urban soils of Kumasi, Ghana, *Environ. Monit. Assess.*, 2017, **189**, 260, DOI: 10.1007/s10661-017-5972-9.

79 N. K. Asare-Donkor and A. A. Adimado, Groundwater quality assessment in the Northern and Upper East Regions of Ghana, *Environ. Earth Sci.*, 2020, **79**, 205, DOI: 10.1007/s12665-020-08956-x.

80 A. O. Awuah and B. Kyereh, Heavy metal contamination in topsoil in mining-plagued communities in the Amansie West District, Ghana, *Soil Sediment Contam.*, 2023, DOI: 10.1080/15320383.2023.2260897.

81 N. U. Uka, E. J. Belford and J. N. Hogarh, Ambient air quality assessment of Kumasi metropolis, Ghana, *J. Ghana Sci. Assoc.*, 2020, **19**, 56–62, https://www.researchgate.net/publication/350691896.

82 C. A. Faseyi, M. K. Miyittah, A. A. Sowunmi and L. Yafetto, Water quality and health risk assessments of illegal gold mining-impacted estuaries in Ghana, *Mar. Pollut. Bull.*, 2022, **185**, 114277, DOI: 10.1016/j.marpolbul.2022.114277.

83 G. Edusei, J. B. Tandoh, R. Edziah and O. Gyampo, Chronological studies of traffic pollution using elemental analysis of tree rings: Case study of Haatso-atomic road, *Pollution*, 2020, **6**, 377–386, DOI: 10.22059/poll.2020.291347.701.

84 L. B. Osei, S. Fosu, S. A. Ndur and S. Y. Nyarko, Assessing heavy metal contamination and ecological risk of urban topsoils in Tarkwa, Ghana, *Environ. Monit. Assess.*, 2022, **194**, 710, DOI: 10.1007/s10661-022-10398-w.

85 E. Bampoe, S. J. Cobbina and D. A. Doke, Assessment of heavy metal levels and associated human health risk in dust from high and low traffic transport stations in the Tamale metropolis, in the northern region of Ghana, *Int. J. Environ. Sci. Technol.*, 2023, **20**, 8497–8508, DOI: 10.1007/s13762-022-04522-z.

86 B. Amponsah, N. O. Boadi, P. O. Sakyi, E. S. Agorku, S. A. Saah, H. Okyere and A. Nyamful, Evaluation of groundwater quality in communities near Sokoban Wood Village, *Heliyon*, 2024, **10**, e32757, DOI: 10.1016/j.heliyon.2024.e32757.

87 P. M. Abdulai, K. Sam, A. P. Onyena, A. N. Ezejiofor, C. Frazzoli, O. C. Ekhator, G. J. Udom, C. K. Frimpong, J. Nriagu and O. E. Orisakwe, Persistent organic pollutants and heavy metals in Ghanaian environment: A systematic review of food safety implications, *Environ. Monit. Assess.*, 2024, **196**, 376, DOI: 10.1007/s10661-024-12500-w.

88 B. D. Asamoah, L. L. Yevugah, L. S. Borquaye, M. Dodd and G. Darko, Spatial distribution, bioaccessibility, and human health implications of potentially toxic elements in mining-impacted topsoils in Obuasi Municipality of Ghana, *Environ. Geochem. Health*, 2024, **46**, 291, DOI: 10.1007/s10653-024-02028-w.

89 K. Agyarko, E. Darteh and B. Berlinger, Metal levels in some refuse dump soils and plants in Ghana, *Plant Soil Environ.*, 2010, **56**, 244–251.

90 G. L. Essilfie, S. Lamptey, R. N. N. Baddoo, G. Amenorpe, W. Hevi, M. Owusu, *et al.*, Food safety in the horticultural sector in Ghana: Challenges, risk factors, and interventions, *Front. Sustain. Food Syst.*, 2023, **7**, 1173677, DOI: 10.3389/fsufs.2023.1173677.

91 L. N. A. Sackey, B. Fei-Baffoe, N. Twum and A. B. Antwi, Assessment of toxic elements in selected fish species in the marine water at Jamestown, Ghana, *Heliyon*, 2024, **10**, e32387, DOI: 10.1016/j.heliyon.2024.e32387.